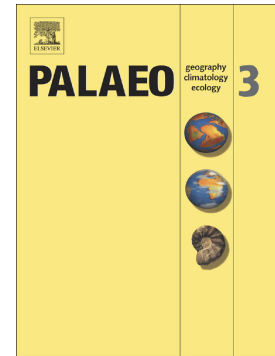


## Accepted Manuscript

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PII: S0031-0182(18)30929-5  
DOI: <https://doi.org/10.1016/j.palaeo.2019.05.010>  
Reference: PALAEO 9188

To appear in: *Palaeogeography, Palaeoclimatology, Palaeoecology*

Received date: 19 November 2018  
Revised date: 30 April 2019  
Accepted date: 6 May 2019

Please cite this article as: R.J. Morley, B.V. Dung, N.T. Tung, et al., High-resolution Palaeogene sequence stratigraphic framework for the Cuu Long Basin, offshore Vietnam, driven by climate change and tectonics, established from sequence biostratigraphy, *Palaeogeography, Palaeoclimatology, Palaeoecology*, <https://doi.org/10.1016/j.palaeo.2019.05.010>

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# High-resolution Palaeogene sequence stratigraphic framework for the Cuu Long Basin, offshore Vietnam, driven by climate change and tectonics, established from sequence biostratigraphy

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## Abstract

The chronostratigraphy of the Cuu Long Basin, offshore Vietnam to the south of the Mekong Delta, is poorly understood, especially for the Palaeogene succession. This paper utilises a comprehensive biostratigraphic database from 46 exploration wells to establish a high-resolution sequence biostratigraphic framework for the Oligocene and upper Eocene based on the identification of 36 transgressive-regressive depositional cycles. They are shown to be climate-driven and correlate to 406 kyr ‘heartbeat of the Oligocene’ eccentricity cycles. Their occurrence has been rigorously cross checked against seismic across the basin. This re-evaluation requires the repositioning of the Oligo-Miocene boundary in the Cuu Long Basin from the C seismic pick to the BI.1 seismic pick.

By integrating sequence biostratigraphic and seismic datasets, the Oligocene can be seen as characterised by two types of depositional sequence. Firstly, thin and repetitive depositional packages, here termed ‘Sequences’ but perhaps better visualised as parasequences, the deposition of which was controlled by cyclically changing climate. Secondly, much thicker packages, each comprising a succession of parasequences separated by unconformities, and which tie to the main seismic divisions within the Oligocene/upper Eocene and were driven by tectonics. The latter are visualised as 3<sup>rd</sup> order sequences, with the parasequences forming 4<sup>th</sup> order sequences.

Correlating the succession of parasequences to the 406 kyr ‘heartbeat of the Oligocene’ isotope cycles allows accurate ages to be proposed for each parasequence boundary, and in doing so an accurate time framework is established for the basin. The first sediments may have been deposited during the latest middle Eocene (Seismic group F/G) at the same time as or just prior to the initial stage of faulting prior to the opening of the South China (East Vietnam) Sea, with



deposition of seismic group E commencing at about 36.6 Ma during the late Eocene. Unconformities reflecting 3<sup>rd</sup> order sequence boundaries are dated at 33.4 Ma, 29.8 Ma and 27.4 Ma.

## 1. Introduction

The Cuu Long Basin lies offshore Vietnam, to the south of the Mekong Delta, on the Sunda Shelf (Fig. 1A). It is orientated from WSW to ENE and is bounded to the south by the Con Son Swell, and to the north by the Vietnamese mainland (Lee *et al.*, 2001; Hung and Le, 2004, Schmidt *et al.*, 2019). It is one of many basins which formed across Sundaland during the mid Cenozoic, with which it shows numerous features in common, but also several differences (Swiecicki and Maynard, 2009; Morley *et al.*, 2011; Morley, 2014; Pubellier and Morley, 2014; Savva *et al.*, 2014).

The structural development of the basin is characterised by rifting, inversion and regional subsidence (Fig. 2), resulting in sediment thicknesses of over 10,000 m in the basin depocentre (Lee *et al.*, 2001, Fyhn *et al.*, 2009; Schmidt *et al.*, 2019). Whereas the adjacent Nam Con Son Basin is clearly characterised by two phases of rifting, with initial rifting during the Eocene and early Oligocene, followed by a sag phase, and then further rifting in the middle Miocene (Matthews *et al.*, 1997; Lee *et al.*, 2001; Morley *et al.*, 2011; Swiecicki and Maynard, 2009), the pattern and timing of rifting in the Cuu Long Basin is less clear (Hung and Lee, 2004; Swiecicki and Maynard, 2009; Schmidt *et al.*, 2019). This paper attempts to clarify the chronostratigraphy of the Cuu Long Palaeogene succession and tries to establish a better correlation with the succession seen in adjacent basins.

**Insert Fig 1 approx here Location map**

For the Miocene and Pliocene, the succession will be discussed elsewhere. For the non-marine Oligocene and upper Eocene, a novel approach is used. The application of sequence biostratigraphic methodology indicates the presence of repeated very high resolution transgressive-regressive cycles the formation of which can be demonstrated to be driven by cyclical climate change, similar to those interpreted for the upper Oligocene in the West Natuna Basin by Morley *et al.* (2007, 2012). It is suggested that the cyclicity is best explained by reference to 406 kyr 'heartbeat of the Oligocene' climate cycles as proposed for the western Pacific by Paalike *et al.* (2006) and Westerhold *et al.* (2014). The regional perspective applied here with wells from basin depocentres to the basin margins ensures that all depositional cycles present in the basin have been sampled. Based on a complete succession of depositional cycles this cyclicity permits the age of the Palaeogene succession to be precisely proposed, and thus the age of the succession, and the timing of major events and unconformities can for the first time be accurately compared to the succession seen in adjacent basins and in relation to phases of sea floor spreading in the South China Sea (also referred to as East Vietnam Sea) (Briais *et al.*, 1992).

The identification of depositional cycles allows seismic packages interpreted in the basin to be subdivided into higher order sequences or parasequences (see below). It can be shown that the

formation of the high resolution parasequences were driven essentially by climate (and hence by sea level) and from parasequence architecture and stacking patterns it is shown that the seismically defined packages are essentially controlled by tectonics. The study thus demonstrates that the effect of eustatic change can be systematically differentiated from tectonic subsidence, and thus resolves a long-standing issue in sequence stratigraphy - of the differentiation of eustasy from tectonic change in the rock record (Wilgus *et al.*, 1988; van Waggoner, 1990; Miall, 1991, 1992).

## 2. Geological background

### 2.1. Cuu Long stratigraphic succession

The Cuu Long succession (Fig. 2) begins with deposits of the Ca Coi and Tra Cu Formations of Eocene to lower Oligocene age that consist of alluvial, fluvial and lacustrine fine to coarse grained sandstones, interbedded with siltstone, shale, thin coals and conglomerates overlying Mesozoic igneous basement. The Tra Cu Formation is mainly referred to as comprising seismic group E, but locally overlies basal packages referred the Ca Coi Formation attributed to seismic groups F and G (Hung *et al.*, 2004; San *et al.*, 2013; Quang and Tham, 2013). The Tra Cu Formation is mostly overlain by shales and siltstones intercalated with sandstone of the Tra Tan Formation, referred to seismic groups C and D. The Tra Tan is interpreted to be fluvial and lacustrine, although deposition in a brackish or intertidal setting is commonly suggested, and a late Oligocene age is applied (Hung *et al.*, 2004; San *et al.*, 2013).

The overlying Bach Ho Formation is generally referred to the lower Miocene and consists of a lower package (seismic group BI.1) of shales and sands, typically interpreted as deltaic to shallow marine, although it lacks foraminifera or other definitive marine fossils. The age of this package is revised in this study. The upper part of the Upper Bach Ho Formation (seismic group BI.2) which often includes the *Rotalia* Shale, contains a monospecific foraminiferal assemblage with common *Ammonia* spp. and is clearly shallow marine and of early Miocene age (Hung *et al.*, 2004; San *et al.*, 2013).

### Insert Fig 2 approx here. Strat summary

Younger sediments comprise sands and shales of the Con Son Formation, generally considered of middle Miocene age, and referred to seismic group BII, and upper Miocene Dong Nai Formation (Seismic group BIII), overlain by the Pliocene to Quaternary Bien Dong Formation which is referred to seismic group A, and which consists of clastics with some carbonates and coals (Hung *et al.*, 2004; San *et al.*, 2013). The Con Son Formation has sparse marine fossils and is essentially paralic. The Dong Nai Formation contains shallow marine benthonic faunas, whereas the common occurrence of planktonic foraminifera within the Bien Dong indicates a more open marine influence.

The Cuu Long Basin naturally divides into eastern and western sub-basins (Fig. 1B). The thickest sediments occur in the southern and central part of the western sub-basin, where

basement has not been penetrated and only a few wells penetrate deposits below the Tra Tan Formation, with most terminating in seismic group D. In the eastern sub-basin on the other hand, the Lower Bach Ho Formation (Seismic Group Bl.1) and the Upper Tra Tan Formation (Seismic Group C) are less well developed, and more wells penetrate the stratigraphically deeper Lower Tra Tan and Tra Cu Formations (seismic groups D and E). Combining datasets from the western and eastern Cuu Long sub-basins provides a very comprehensive perspective of the detailed stratigraphy of the entire Oligocene and upper Eocene succession.

## **2.2. Tectonic setting**

Basin initiation was during the Eocene, relating either to the collision of the Indian Plate with Asia, which resulted in extensive tectonic movement across the Sunda region, often graphically explained as causing the extrusion of Indochina (Taponnier *et al.*, 1982; Rangin *et al.*, 2001) or to slab pull relating to the closure of the Proto-South China Sea (Clift *et al.*, 2008; Hall *et al.*, 2017). Most authors recognise that the Tra Cu Formation represents the synrift phase of deposition. However, published and unpublished reviews present different perspectives of the tectonic setting of younger formations. Lee *et al.* (2003) suggest that rifting continued to the top of the Tra Tan Formation at the end of the Oligocene, after which the basin was subject to subsidence, whereas Hung and Le (2004) suggest that rifting continued through the Bach Ho Formation during the early Miocene, with thermal subsidence from the middle Miocene onward. Swiecicki and Maynard (2009) suggest inversion within the Tra Tan Formation, and unpublished compilations suggest multiple phases of inversion within the Tra Tan and Lower Bach Ho Formations. More recently, Schmidt *et al.* (2019) suggested the waning of rifting during the mid-Oligocene, followed by late Oligocene inversion. Clearly, improved chronostratigraphy would help clarify the tectonics of the basin.

## **3. Database and methods**

The Vietnam Petroleum Institute (VPI) routinely studies petroleum exploration wells from the Cuu Long Basin for palynology, foraminifera and nannofossils. This review is based on the evaluation of biostratigraphic data from 46 datasets (Fig. 1B) selected from over 120 biostratigraphic studies undertaken in the basin. The selected wells were each studied for palynology with a total of 4750 mainly cuttings samples being appraised. Eight wells were examined in their upper part for foraminifera and three for nannofossils. Most wells were studied from the top of the Bach Ho Formation to total drilled depth, most reaching basement except in the basin depocentre.

Palynological evaluations were mostly undertaken using drill cuttings at 10 m sample spacing, and a few sections were sampled at 20 m spacing. Some wells were studied in much greater detail, at 5 m spacing, and these studies have been critical to this evaluation since sampling was sufficiently close to sample patterns of high-resolution climate cyclicity. These wells are included within the 11 Wells (A-K) which provide the main reference sections for the study.

Samples for palynology were processed by standard methods to concentrate the palynomorphs (Phipps and Playford, 1984) but with additional sieving at 5 microns to remove fine

debris. All determined palynomorph taxa were logged and the total number of palynomorphs per slide estimated. The total count varies depending on the abundance of fern spores and algal palynomorphs, which can be extremely abundant (often over 90% of the recovery) but typically logging has been undertaken until about 100 *terra firma* pollen have been recorded.

Foraminifera and nannofossils were studied in the Bach Ho and younger formations using the same samples as selected for palynology. Samples for foraminifera were analysed semi-quantitatively, whereas for nannofossils the number of specimens in four traverses was determined for each sample.

Gama-ray curves and six regional seismic lines were utilised (Fig. 1B). The seismic lines link the majority of the wells studied for biostratigraphy. The interpreted sequence biostratigraphic packages were systematically compared to seismic to confirm their continuity and establish their spatial representation.

### **3.1. Cores versus cuttings**

It is generally considered that biostratigraphic analyses of cuttings samples is less satisfactory than analysis of conventional or sidewall cores since cuttings samples can be contaminated by caved material and also do not relate to a specific depth but to a range of depths. However, for sequence biostratigraphic work, systematically collected cuttings samples tend to show broad trends more readily than core samples. This is because an assemblage from a core sample will relate to one specific lithological horizon, whereas a cuttings sample from the same depth will provide an 'average' assemblage from a succession of lithologies. This can be demonstrated with a 'core to cuttings' correlation, which showed that to reproduce the broad trends seen in cuttings samples using cores requires much more dense sampling (Morley *et al.*, 2007).

### **3.2. Data evaluation**

Biostratigraphic data from petroleum exploration wells is complex. For palynology, a typical well section from Cuu Long basin will yield upwards of 200 palynomorph taxa, and include diverse pollen and spores, and often abundant freshwater dinocysts and other algae. Pollen is derived from lake margin, coastal plain and mangrove swamp settings, but also from lowland and montane vegetation that grew in the upper reaches of the catchment supplying sediment. Spores are also abundant, mainly being derived from swamp vegetation and riversides. To simplify the evaluation process to determine which pollen and spore spectra are useful for chronostratigraphy, and which are useful for environment interpretation, pollen and spores are grouped according to the ecology of the plants from which they were derived, following Morley (2000), Morley and Morley (2013) and Ashton (2014) and references therein. The main palynomorph groupings are: mangrove and lake margin pollen including *Acrostichum* spores; 'hinterland' pollen; determinable pteridophyte spores excluding *Acrostichum*; other generalised spores; and algae/other palynomorphs (Fig. 3). A detailed discussion of synonymies of these taxa and taxon groupings, and of the ecology of main parent taxa is presented in Appendix 1.

**Insert Fig 3 approx here (Pallynomorph groupings)**

Changes in hinterland pollen assemblages are likely to reflect climate change (perhaps driven by local tectonic or global climate change), which may be useful for identifying basinwide regional events for correlation, following the approach outlined in Morley (1991). Hinterland pollen groups and some lake margin swamp taxa were then evaluated for palynomorph abundance changes that can be followed across the basin, picking out 'sensitive species' in the sense of Fournier (1981) for regional correlation. The resulting events have been used to build a succession of local palynological zones, based on regionally consistent abundance changes of specific taxa, and are discussed in detail in section 4. The zonation obtained allows the Oligocene and upper Eocene to be divided into eleven local palynological zones and subzones applicable to the Cuu Long Basin. Subsequent work has shown that these zones are also in part applicable to the Song Hong Basin in northern Vietnam.

**3.3 Data presentation and 'pollen sums'**

The four main components of assemblages; pollen from hinterland '*terra firma*' settings, pollen from lake margin settings, spores from lake margin fern swamps and lacustrine algae (Fig 4), may overwhelmingly dominate depending on facies as a result of the Neaves effect (Chaloner and Muir, 1968). Due to such super-dominance, presentation of data to effectively illustrate the cyclicity requires careful thought. The standard approach to presentation of algal palynomorph data is to include algae within the pollen sum (Maher, 1972) presenting algae as a percentage of total palynomorphs (Fig. 5 algae column 1). However, in the sections studied here, especially within the lower part of the Lower Bach Ho and Tra Tan and Tra Cu Formations, algal palynomorphs may be very abundant during low lake level periods and obscure the cycles (e.g. Sequence 22 in Fig. 5). On the other hand, in the upper part of the Lower Bach Ho Formation, low palynomorph recoveries may result in quite spurious spectra, such as Sequence 28a in Fig 5. Presenting the total number of algae present per slide clearly shows the positions of algal maxima when palynomorph recovery is good, with recoveries of over 5000 algal palynomorphs per slide, as within the lower part of the Lower Bach Ho Formation (Fig. 5 algae column 3), but in the lower part of the Tra Tan Formation, where palynomorph recovery is reduced due to increased thermal maturity as a result of burial, making palynomorphs more difficult to extract, cycles may again be poorly reflected. The depositional cycles are most clearly reflected irrespective of the overall palynomorph recovery when algal palynomorph percentages are calculated *outside* the '*terra firma*' pollen sum (sensu Faegri and Iversen, 1964), resulting in 'percentages' of between 0-5000% (Fig. 5 algae column 2). If palynomorph groups that are strongly controlled by facies are all calculated in this manner, calculating *outside* the *terra firma* pollen sum, the resulting plots are affected neither by factors relating to the interdependence of percentage plots, nor to differential palynomorph recovery relating to differential recovery or depth of burial issues, and the process of cycle differentiation and environment interpretation is greatly simplified. It is thought that this provides a proxy for the approximate acreage of open lake facies within the basin. In this

study, plots of algal palynomorphs are calculated outside the *terra firma* pollen sum to show cyclicity patterns using algal palynomorph and fern spore spectra. In practice, it is useful to examine the algal palynomorph and pteridophyte spore spectra using a variety of presentation styles to understand the different nuances regarding the nature of the cycles facilitating cycle interpretation irrespective of the position of a well profile within the basin.

**Insert Fig 4 approx here (environment classification)**

**Insert Fig 5 approx here (Pollen sums)**

### **3.4. Environment interpretation in fluvial and lacustrine facies**

The detailed interpretation of depositional environments has allowed the recognition of high frequency depositional cycles throughout the succession studied. These cycles are discussed in Section 6. Depositional environments are mostly reflected in abundance changes of pollen and spores that are likely to have been sourced from vegetation growing along lake margins, or rooted and floating aquatics, and from algae that would have occurred in standing bodies of water. The palynomorph groupings that provide most information on depositional environment are the 'lake margin' and 'pteridophyte spore' groups, freshwater algae and dinocysts.

Interpretation of lacustrine facies in low latitude Cenozoic successions using biostratigraphy often falls short of expectations, often with misinterpretations with respect to salinity levels (and hence marine connectivity), especially when sections contain supposed 'mangrove' palynomorphs, such as the pollen precursors to *Sonneratia*, *Acrostichum* spores, and algal palynomorphs referable to *Bosedinia*. Morley and Morley (2013) illustrated that pollen of *Sonneratia* precursors, such as *Florschuetzia trilobata*, can commonly occur in freshwater lacustrine settings. The fern *Acrostichum* is characteristic of mangroves across South East Asia today, but it is a facultative mangrove taxon since it can occur far inland in completely freshwater settings, such as at Lake Kerinci (900m asl) in Sumatra, Indonesia (van Steenis and Schippers-Lammertse, 1965). In the mid Cenozoic of Europe it was a pioneer of floodplain areas (Collinson, 2002, Moreno-Dominguez *et al.*, 2016) and it is in this setting that it is thought to have been most prolific in the Oligocene Cuu Long Basin. *Acrostichum* spores cannot be used alone as an indicator of mangrove swamps, or of tidal influence.

With respect to algal palynomorphs such as *Bosedinia*, Morley *et al.* (2007) demonstrated a strong negative correlation between the occurrence of *Bosedinia* and the brackish water foraminifer *Miliammina* from the detailed evaluation of cores from West Natuna Oligocene brackish/lacustrine sediments. This study firmly indicated that *Bosedinia* was entirely restricted

to freshwater environments with respect to habitat, although it is widely used to suggest brackish conditions in unpublished petroleum industry reports across South East Asia.

In this study, the persistent absence of foraminifera and extremely sporadic occurrence of obligate mangroves is taken as evidence for freshwater deposition. Fluvial and lacustrine environments have been interpreted by comparing the percentage abundance and abundance per slide for 'lake-margin pollen', 'swamp fern spores' and 'lacustrine algae' in relation to lithology following Fig. 4. This model essentially follows suggestions made for Sunda freshwater facies by Morley and Morley (2013).

Fluvial and lacustrine facies are thus differentiated as follows:

Fluvial sediments are suggested in sections characterised by fluctuating abundances of palynomorphs, with dominance of pollen of plants from *terra firma* settings, such as grasses, conifers, *Crudia*, dipterocarps, *Schoutenia* and spores of the climbing fern *Stenochlaena palustris*. Assemblages are also characterised by the low representation of pollen of lake-margin swamp taxa and 'terrestrial wet' fern spores, and the absence or rarity of freshwater algal palynomorphs. Lithologies are typically sands with subordinate shales.

Lake-margin seasonally inundated swamp sediments, which include overbank and channel facies, are suggested in sections with common to abundant *Barringtonia*, *Brownlowia* type, cf. *Livistona* pollen, *Acrostichum* spores and the form taxa *Florschuetzia trilobata*, *Trilobapollis* and *Verrutricolporites pachydermus*. *Ceratopteris* spores are regularly present, but not dominant. Lithologies are typically shales with subordinate sands. Common *Barringtonia* pollen suggests similarity with the seasonally inundated swamp forests of the Tonle Sap (Dy Phon, 1981). Intervals with common *Acrostichum* spores are thought to reflect ephemeral or unstable high energy freshwater settings, as suggested by Moreno-Dominguez *et al.* (2016). This facies typically yields common freshwater algae (up to 50% of total palynomorphs), but combined palynological and sedimentological analysis (R. J. Morley, unpublished) of cores from the Tra Tan Formation suggest that up to 50% freshwater algae may occur within overbank deposits. The Tonle Sap in Cambodia is thought to provide a good analogue for the facies, with a central permanent lake, and a seasonally inundated peripheral area with overbank sediments.

Lacustrine shoreface facies with (?floating) fern swamps are suggested when algal palynomorphs are sufficiently common to indicate deposition in a permanently inundated setting (algae form between 50% and 90% of total palynomorphs), yet pollen and spore distributions suggest that some aquatic plants may be locally rooted (Janssen, 1966), or form lake margin floating mats. In addition to the very high representation of algal palynomorphs, these facies also typically contain very abundant *Ceratopteris* spores. In addition, *Merremia* and Onagraceae pollen, suggesting marsh vegetation, may be well represented. Lithologies are mainly shales with subordinate sands. To permit display of trends in shoreface facies without undue interference of pollen sums due to interdependence of percentage data, it is useful to examine the abundance of

algal and fern spore trends by plotting both *outside* the pollen sum based on total freshwater pollen.

The sheer abundance of *Ceratopteris* spores in some assemblages within shoreface facies suggests that *Ceratopteris* may have formed an extensive consocieties, most likely as rooted swamps along lake margins, or possibly as floating mats. There are very few settings today where *Ceratopteris* is so abundant as to produce the numbers of spores seen here. One possible location is the Hisiu Lagoon, a series of muddy, seasonally flooded lakes forming behind beach ridges on the southern margin of the Huon Peninsula in Papua New Guinea (Osbourne, 1996; Morley and Morley, 2013). The expected Holocene analogues in Indochina (e.g. Tonle Sap, Songkla lakes) do not yield significant numbers of *Ceratopteris* spores (Horton *et al.*, 2009; Bishop *et al.*, 2003).

Shallow or proximal lake facies are suggested where algal palynomorphs are numerically abundant and form between 50 and 95% of palynomorph assemblages, with *Botryococcus* dominant and terrestrially derived pollen and spores remaining abundant, suggesting a proximal lacustrine depositional setting. A 'shallow' lacustrine setting is inferred based on this association. Lithologies consist mainly of shales.

Assemblages with abundant palynomorphs which are overwhelmingly dominated by freshwater algae (95%+), with either *Pediastrum* spp. or *Bosedinia* spp. dominant, are considered to reflect deposition in a more distal, deeper setting and are interpreted as reflecting 'deeper lake' facies. *Bosedinia* spp. are thought to become dominant in the deepest or most distal lacustrine facies since they tend to dominate when the pollen/spore content per slide is less than for samples with *Pediastrum* dominant. Lithologies consist mainly of shales but with some sands.

#### 4. Palynological zonation

A broad stratigraphic division of the succession is possible based on the identification of palynological zones. For the Upper Bach Ho Formation, the 'PR' Malay Basin zones of Yakzan *et al.* (1996), apply with age attributions modified according to Morley *et al.* (2014). The palynological zonation proposed here for the late Eocene, Oligocene and earliest Miocene has been constructed based on the VPI database, renaming the Malay Basin zones (Fig. 6, 7, 8). Zones use the prefix 'CL' to show that they refer to Cuu Long Basin, with early Miocene zones prefixed 'M' and Oligocene zones prefixed 'O'. Interpreted zones are described from youngest to oldest in Table 1.

**Insert Fig 6 here (W Cuu Long zones)**

**Insert Fig 7 here (E Cuu Long zones)**

**Insert Table 1 here**



The stratigraphic base of *Florschuetzia levipoli*, derived from the backmangrove tree *Sonneratia caseolaris*, indicates the base of palynological zone PR9a in the Malay Basin, and occurs within the topmost part of the Upper Bach Ho Formation in the Cuu Long Basin. This datum has usually been placed intra early Miocene (Germeraad *et al.*, 1968; Ho, 1978; Yakzan *et al.*, 1996) but recent studies from outboard Sarawak, in which planktonic foraminifera and nannofossils are regularly present together with common palynomorphs through the lower Miocene, show that the evolutionary appearance of *F. levipoli* is close to the base of the early Miocene, at about 21.5 Ma, within planktonic foraminiferal zone N4 and close to the top of nannofossil zone NN1. It is thus just above the base of the early Miocene (Morley *et al.*, 2015).

The stratigraphic base of *Florschuetzia semilobata* occurs near the base of the Upper Bach Ho Formation and the interval between the deepest *F. levipoli* and base *F. semilobata* can be referred to Malay Basin palynological zone PR8 which is equivalent to Cuu Long zone CLM-1. *Bosedinia* spp. regularly occur just below this, suggesting palynological zone PR7 or older (Cuu Long zone CLO-9 and older) for the Lower Bach Ho Formation. This suggests that the Oligocene-Miocene boundary corresponds to the base of the Upper Bach Ho Formation.

Dating the Oligocene and late Eocene in Cuu Long has always been problematic, as there are few Oligocene palynomorphs that are strictly index fossils. The highest stratigraphic occurrence of regular *Cicatricosisporites dorogensis*, and highest *Verrutricolporites pachydermus*, which form an event at the top of the Tra Tan Formation, is generally used to locate the top of the Oligocene (Chung *et al.*, 2015), but *C. dorogensis* occurs in low numbers to the top of the Lower Bach Ho Formation and this top is thought to provide a better position for the Oligocene-Miocene boundary. In the Gulf of Thailand, *Verrutricolporites pachydermus* occurs commonly in the lower Miocene and so cannot be used (R.J. Morley unpublished). The stratigraphic base of *Ceratopteris* spores (form taxon *Magnastriatites howardi*) is also critical for determining the age of the succession, with an evolutionary appearance at 35 Ma within the late Eocene (Witts *et al.*, 2012). The oldest occurrences in Cuu Long are within the lower part of the Tra Cu Formation (see below).

**Insert Fig 8 here (Zone summary)**

## 5. The Oligocene-Miocene boundary

Traditionally, the Oligocene-Miocene boundary has been placed at the top of the Tra Tan Formation (Fig. 2). In this study, it is considered that a much more realistic position for the Oligocene-Miocene boundary is at the base of the 'B1.1' seismic interval. The reasoning for this is as follows:

The evolutionary appearance of *Florschuetzia levipoli* is now known to occur within planktonic zone N4 (Morley *et al.*, 2015) rather than during the 'mid' part of the early Miocene as often suggested on stratigraphic charts as noted above.

Top Oligocene was previously picked at the highest stratigraphic occurrence of regular *Verrutricolporites pachydermus* and the highest occurrence of regular *Cicatricosisporites*

*dorogensis* in palynological zone CLO-8, first occurring within seismic interval C. There are thus no regular miospore markers between the base of *Florschuetzia levipoli*, and the top of *V. pachydermus*/*C. dorogensis* other than rare *C. dorogensis*. The absence/rarity of common markers in this interval is thought to be due to oxidation of palynomorphs at the time of deposition.

If top Oligocene is at top Tra Tan Formation, then the short-lived PR8/CLM-1 interval spans the whole of seismic interval B1.1 with a very high sedimentation rate of 180 m per 100 kyr, equivalent to that of the current Bengal Fan (Shwenk *et al.*, 2007). This seems to be inappropriate as in adjacent basins, the basal Miocene shows much slower deposition during this period. The likelihood is that the Oligocene-Miocene boundary occurs at the base of palynological zone CLM-1, at or near the top of the Lower Bach Ho Formation, directly above the highest *Cicatricosisporites dorogensis*.

## 6. Depositional cycles

The Bach Ho, Tra Tan and Tra Cu Formations are characterised by repeated, and mostly equi-thickness depositional cycles. They are most clearly reflected in distal locations, by changes in abundance of freshwater algal palynomorphs (Fig. 4), but in proximal locations, they may be suggested from cyclical fluctuations in fern spore abundance, or lake margin swamp assemblages.

Systematic interpretation of depositional cycles across the basin suggests that they can be correlated from basin depocentre to basin margin. Their very rhythmic character suggests that the cycles are not driven by tectonics, but by an independent control, such as climate, that episodically affects sediment supply and lake water level. To reveal the nature of cyclically fluctuating climate change, the broad patterns of vegetation change suggested from pollen from vegetation growing in ‘*terra firma*’ settings has been interpreted in terms of the vegetation classification for the region by Ashton (2014), summarised in Table 2. Understanding the controls on these depositional cycles, their number, and their differential representation across the basin, provides the key to understanding the age and tectonic development of the basin.

### Insert Table 2 here (classification of vegetation types)

The depositional cycles are interpreted as ‘transgressive-regressive’ sequences. The base of each cycle is placed at the base of the most proximal facies interpreted, with the precise position located at a break in the gamma log suggesting a basinward facies shift, i.e. at the base of a sand if present. The maximum flood is positioned at the highest concentration of freshwater algae, coinciding with a shale, or at a maximum of lake margin pollen in proximal locations where algae may be poorly represented. By examining assemblage changes in pollen from *terra firma* settings, especially in sections which have been analysed using 5 m sample spacing, trends with respect to climate change can be examined to determine if depositional cycles coincide with trends of changing climate.

The depositional sequences within the Bach Ho, Tra Tan and Tra Cu Formations are numbered ?2 to 31, with some being subdivided into a/b. These can be interpreted and correlated across the basin. Eight well sections from different sub-basins are needed to illustrate the character and frequency of the cycles (Fig. 9, 10).

The numerical attribution to each cycle is determined or ‘fingerprinted’ by reference to their position relative to the interpreted Cuu Long palynological zones, which are described in Table 1.

The transgressive-regressive cyclical packages can be divided into seven different groups as follows. They are described from youngest to oldest as the younger packages yield richer assemblages and interpretations are more confident. With reduced recovery and confidence of interpretation in the oldest packages.

### **6.1. Uppermost Lower and Upper Bach Ho Formation, Seismic group BI.2 and topmost BI.1, Sequences 31-29**

Sequences 31-29 span the revised Oligocene-Miocene boundary and are clearly characterised in Well E (Fig. 9, 11). Sequences 30 and 31 occur between Seismic Horizon BI.1 and BI.2 and comprise the Upper Bach Ho Formation dated as lowest lower Miocene. Sequence 29 occurs within the topmost part of the Lower Bach Ho Formation in the topmost upper Oligocene (containing rare *Cicatricosisporites dorogensis*). All three sequences show similar palaeoenvironment trends with an initial widespread lake facies followed by infill with prograding highstand deltas. The sequences are mainly characterised by maxima of the algal palynomorphs *Pediastrum* spp. and *Botryococcus* spp. The sequence stratigraphic succession in these units is particularly clear, and so they are described below in some detail to illustrate the typical relationship between sequence stratigraphic surfaces and palynomorph assemblages.

#### **Insert Fig 9 approx here (W Cuu Long cycles)**

Sequence 29 has a maximum of freshwater algae in its lower part at the time of maximum development of lacustrine facies, indicating the time of maximum flood and corresponding to a high amplitude seismic reflector. This is followed by maxima of *Acrostichum* and *Ceratopteris* spores with the upsection increase in abundance reflecting the development of lake margin vegetation as the highstand delta prograded into the basin. The BI.1 seismic pick corresponds to the Sequence 29 sequence boundary. This sequence occurs within the upper part of palynological zone CLO-9C.

Sequence 30 is characterised by a maximum of freshwater algae in its basal part, corresponding to the maximum flood and a very high amplitude seismic reflector. A maximum of *Acrostichum* spores immediately follow this, again marking the development of lake margin vegetation and a prograding highstand delta, followed by a maximum of *Ceratopteris* spores in the highstand itself (Fig. 9). Foraminiferal analysis (not performed for Well E) typically shows low numbers of indeterminate agglutinated foraminifera and some *Ammonia* spp, reflecting the onset of direct marine influence in the basin at the beginning of the early Miocene. This sequence corresponds approximately to palynological zone CLM-1.

In Sequence 31, *Acrostichum* and *Ceratopteris* spores, algal palynomorphs and dinocysts show clear maxima in the same horizon, suggesting marine influence at the maximum flood that was immediately followed by delta progradation. The maximum flood corresponds to the BI.2 seismic pick, suggesting that the top of the Bach Ho Formation should be positioned at the top of the sequence, rather than being positioned on the seismic pick. The package is characterised by a distinct maximum of *Arenga* pollen indicating pollen zone CLM-2 (Fig. 6, 8). This package often yields common *Ammonia* spp, but without other calcareous foraminifera suggesting persistent marine influence, and correlating with a dinocyst acme. This package forms the *Rotalia* Bed of Fig. 2. Note that although Sequences 29-31 are very clearly differentiated from their palynological character, they are poorly reflected by the gamma log, emphasising that in mud-rich depositional settings, there need not always be a clear relationship between lithology and systems tracts, at least as reflected by the gamma log. The base occurrence of *Florschuetzia levipoli* occurs at the base of this package, indicating an age of about 21.5 Ma, suggesting a reduction in sedimentation rate at the beginning of the Miocene.

Sequences 30 and 31 are characterised by moderate numbers of 'peat swamp' pollen, such as *Durio* type and *Alangium* as well as *Arenga*, occurring together with pollen of the seasonally dry *Lagerstroemia*. This suggests the presence of semi-evergreen forest in *terra firma* settings, suggesting a moist climate but with a long (6 month) dry season at the beginning of the early Miocene (Table 2).

For Sequence 29, the 'peat swamp' elements are missing, and *Pinus* pollen is abundant, suggesting that the dominant vegetation of *terra firma* settings is pine woodland, indicating a significantly drier climate at the end of the late Oligocene compared to the early Miocene.

**Insert Fig 10 approx here (E Cuu Long cycles)**

**Insert Fig 11 here (climate cycles Seg 29-31)**

## **6.2. Lower Bach Ho Formation, Seismic Group BI.1, Sequences 28b-27a**

Sequences 27a-28b form the upper part of the Lower Bach Ho Formation and are distinctive in that they generally yield very poor palynomorph recovery especially in marginal settings. In more basinal settings palynomorphs tend to be regularly present at the time of the maximum flood, and in the basin depocentre moderate to good palynomorph recovery occurs throughout. For this reason, the depositional cycles are defined in the wells at the basin depocentre (Fig. 9, well A and Fig. 10 well F). These sequences occur within palynological zone CLO-9C.

Through Sequences 28b to 27b, the maximum flood is characterised by the alga *Botryococcus* spp and sometimes *Pediastrum*, but for Sequence 27a, *Bosedinia* spp. dominate in the basin

depocentre. Fern spores, dominated by *Ceratopteris*, are often very abundant (Well C, Fig. 12) and are thought to reflect widespread lake margin fern-dominated swamps or very shallow lakes with floating mats dominated by swamp ferns. There are four depositional sequences within this interval (Well A, Fig. 9 and F, Fig. 10). The low palynomorph recovery through this interval, except in the basin depocentre, is thought to be due to a seasonally dry climate at the time of the Oligocene thermal maximum. This suggestion is supported by hinterland pollen assemblages, which are characterised mainly by *Pinus* pollen, suggesting dry pine woodland (Fig. 12). However, it is also thought that the lakes were characterised by seasonally fluctuating water levels, as in Tonle Sap today.

### **6.3. Lower Bach Ho Formation, Seismic group B1.1, Sequences 26b-23**

Sequences 26b to 23, from the lower part of the Lower Bach Ho Formation, are characterised by maxima of the freshwater dinocyst *Bosedinia* spp. at the time of the maximum flood, especially in more basinal wells, such as Well A (Fig 9) and F (Fig. 10). They are also characterised by maxima of *Barringtonia*, and *Brownlowia* type pollen, the latter in Sequences 25 and below, and other pollen of lake-margin taxa, such as the extinct sonneratioids *Florschuetzia trilobata* and *Verrutricolporites pachydermus*. Also, *Ceratopteris* spore maxima continue to occur extensively, suggesting that fern-dominated swamps and floating vegetation mats surrounded the lakes. The abundance of *Barringtonia* pollen suggests seasonally inundated swamp forests such as those which presently surround the Tonle Sap (Dy Phon, 1981), whereas the presence of common *Lagerstroemia* and dipterocarp pollen, with somewhat reduced *Pinus* pollen frequencies compared to sequences 27a to 29, suggest a somewhat wetter, but still strongly seasonal regional climate, probably similar to that of present day tall deciduous forests (Table 2). Sequences 26a/b and 25a/b refer to palynological zone CLO-9B, whereas Sequences 24 to 23 correlate with palynological zone CLO-9A.

### **6.4. Upper Tra Tan Formation, Seismic group C, Sequences 22-17**

Sequences 22-17 include six depositional packages and are from the Upper Tra Tan Formation. They are characterised by typically strong maxima of algal palynomorphs, especially of *Bosedinia* spp. (Fig. 9), suggesting widespread lakes at the time of maximum flood. These lakes were especially well developed within the western Cuu Long Basin. The sequences are also characterised by the common occurrence of *Calamus* type pollen, which identifies palynological zone CLO-8 (Fig. 6, 8), but this reduces in abundance within Sequences 17 and 18 (palynological zone CLO-7). There is also a reduced representation of terrestrially derived pollen compared to the overlying sequences (suggesting a more distal depositional setting), and fewer *Ceratopteris* spores, suggesting that fern-dominated swamps and floating mats were only locally developed.

Sequence 22 contains the most consistent representation of algal palynomorphs across the entire basin, suggesting that this package forms the most transgressive unit of the Oligocene. The maximum flood of Sequence 22 correlates directly with seismic pick C (Fig. 9), but where Sequence 22 thins, seismic pick C correlates to the overlying Sequence 23 sequence boundary. The common

occurrence of *Calamus* type pollen, and sometimes 'peat swamp' elements, together with common dipterocarp pollen, but greatly reduced *Pinus* pollen compared to the overlying succession (Fig. 12), suggests a wetter climate than for sequences 23-25b. The assemblages suggest semi-evergreen forests of Ashton (2014). For Sequences 18 and 17, reduced *Calamus* type pollen and increased *Lagerstroemia* and *Pinus* within palynological zone CLO-7, suggests a slightly drier climate, characterised by deciduous forest or pine woodland (Table 2).

#### **6.5. Lower Tra Tan Formation, Seismic group D, Sequences 16b-14a**

Sequences 16b to 14a form the upper part of the Lower Tra Tan Formation. They differ from those overlying in having increased concentrations of terrestrially derived pollen and spores, together with distinct maxima of freshwater algae, and with dominance of either *Botryococcus* spp., *Pediastrum* spp. or *Bosedinia* spp. suggesting widespread variation in the character of lakes spatially and from sequence to sequence. Lakes were very widespread during deposition of these sequences, especially during Sequence 16a. Seismic pick D, reflecting a period of inversion with erosion, ties with the top of this package, and thus to the sequence boundary of the sequence directly overlying, that could range from Sequence 17 to 21. This succession is well represented in the eastern Cuu Long Basin.

The sequences yield regular pollen of Dipterocarpaceae, and *Riccia* type spores, and common *Pinus* pollen indicating palynological zone CLO-6 (Fig. 7, 8). *Pinus* is less common in Sequences 14a/b. The abundance of dipterocarp and *Lagerstroemia* pollen with common *Pinus* through Sequences 16b to 15 suggests deciduous dipterocarp forests with widespread *Pinus* in *terra firma* areas. This is interpreted as 'Pine-dipterocarp' forest which most likely is a well-drained variant of tall deciduous forests of Ashton (2014).

#### **6.6. Lower Tra Tan Formation, Seismic group D, Sequences 13b - 11**

Sequences 13b to 11 typically contain common cf. *Livistona* pollen, indicating palynological zone CLO-5. *Livistona* is a palm characteristic of freshwater swamps in Malaysia and Indochina, and suggests that during this period lakes were reduced, and lake margin swamps more widespread. Lake margin fern swamps were also well developed at this time based on the abundant occurrence of *Ceratopteris* spores. The common occurrence of pollen of Dipterocarpaceae, together with regular *Lagerstroemia* and the low representation of *Pinus* suggests a seasonally dry climate supporting tall deciduous forests in *terra firma* areas. This package is missing from some areas following basin inversion.

#### **6.7. Tra Cu Formation, Seismic group E, Sequences 9-2**

Sequences 9-2 occupy the initial phase of infill of the basin and palynomorph recovery is generally poor, firstly because facies are mainly high energy, and secondly the depth of burial results in poorly preserved palynomorphs. The packages are mainly characterised by fluvial facies with short-lived intervals with common algal palynomorphs at the time of maximum flood. These

packages are often poor in lake margin pollen but rich in *Stenochlaena palustris* spores, suggesting more widespread fluvial facies and the absence of lake margin swamps. These sequences are referred to palynological zone CLO-4. The succession is best represented in the eastern Cuu Long Basin. Hinterland palynomorph assemblages are characterised mainly by pollen of the temperate and montane angiosperm family Fagaceae.

#### **6.8. Ca Coi Formation, Seismic Group F/G**

The basal lithologies in Cuu Long consist of poorly developed, indurated mainly sandstones attributed to Seismic group F/G (San *et al.*, 2013) and here arbitrarily placed within Sequence 1. Their palynomorph recovery is poor, and so the package is not discussed here, but the reader is referred to Quang and Tham (2013) for further details.

#### **6.9. Controls on cyclical deposition**

The very cyclical character of these depositional packages suggests that they are not driven by tectonics, but by an independent control, such as episodically changing climate, which could intermittently affect sediment supply and lake water levels. Within the Bach Ho and Tra Tan Formations palynomorph recovery is sufficiently good, and with closely spaced samples facilitating examination for evidence of cyclical climate change. This can be assessed from evaluation of the 'hinterland' pollen component, derived mainly from *terra firma* vegetation, and comparing trends with the interpreted depositional cycles.

The section evaluated in Well E was studied using 5 m sample spacing (Fig. 11) and good palynomorph recovery allows intra-cycle climate changes to be evaluated, and reveals three clear cycles which are reflected by changes in hinterland pollen, each showing a change from increased 'seasonal climate' pollen (mainly *Pinus*) or 'temperate gymnosperm' pollen (mainly *Tsuga*) in the lower part of a cycle, to more common rain forest elements in the upper part of each package. This suggests that the high frequency regional climate changes correlate closely to the transgression and regression of lacustrine facies, and that although the 'background' climate is thought to have supported semi-evergreen forests during deposition of these sequences, the climate at the beginning of a cycle was probably drier, and supported pine-dipterocarp forest. This indicates that the depositional cycles are driven by climate rather than tectonics.

**Insert Fig 12 here climate cycles 20-29**

#### **7. 'Heartbeat of the Oligocene' climate cycles**

The Oligocene climate has been studied in detail in the Equatorial Pacific by Paalike *et al.* (2006) and Westerwald *et al.* (2014) for stable isotopes. Using closely spaced  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  sampling, they suggest that the global climate during the Oligocene was driven by 406 kyr eccentricity cycles, which they consider form the 'heartbeat of the Oligocene' with respect to climate. They also note that there is a 1.2 Ma cyclicity which they interpret to correlate to phases of Oligocene glaciation. Similar cyclicity has been noted in the Oligocene and upper Eocene of the Solent Group in the Isle of Wight (Gale *et al.* 2006), and has also been suggested to occur in the West Natuna Basin by Morley *et al.* (2009).

The regular and repeated nature of cycles in the Cuu Long Basin succession suggests astronomical control. Cyclicity of 106 ka, 406 ka and 1.2 Ma are considered as possible drivers for the Cuu Long depositional cycles. The cumulative maximum thickness of Palaeogene sediments in the Cuu Long Basin, based on the 46 wells evaluated exceeds 4400 m. If cycles are driven by 1.2 Ma tilt cyclicity, then the Palaeogene succession should span 27 Ma and include the whole of the Eocene with a very low sedimentation rate of 12.5 m per 100 kyr (Fig. 13). This is clearly not the case. For 106 kyr cyclicity, the Palaeogene succession would have been deposited in just 2.86 Ma and the average sedimentation rate would have been 150 m per 100 kyr, higher than the highest sedimentation rates in the middle Miocene Mahakam Delta (Marshall *et al.*, 2015; Morley, 2015) or Bengal Fan (Shwenk *et al.* 2007). This also is unlikely. If the depositional cycles were driven by 406 kyr eccentricity cycles, then the Palaeogene succession would have been deposited in 14 Ma, with the oldest sediments being deposited in the late Eocene, at about 37 Ma and with sedimentation rates of 37.6 m per 100 kyr. The age of 37 Ma for the initiation of sedimentation would fit very well with the evolutionary occurrence of *Ceratopteris* spores (form taxon *Magnastriatites howardi*), which are likely to be in situ in sequences 6 upwards (Fig. 13). Some specimens occur below this but are rare and probably caved. The evolutionary appearance of this taxon in the Cuu long Basin would fit closely with its oldest well-dated occurrence in outcrop sections in the Tanjung Formation in Kalimantan, appearing at 35 Ma (Witts *et al.*, 2012), where its evolutionary appearance marks the base of palynological zone E9 (van Gorsel *et al.*, 2014).

#### **Insert Fig 13 approx here dating the cycles**

Studies on outcrops of several short Eocene/Oligocene lacustrine successions in China suggest that Chinese lacustrine successions are characterised by 100 kyr Milankovich cyclicity (Li *et al.*, 2012). Cyclogram analysis, that involves spectral analysis of gamma logs (Nio *et al.*, 2005) has been undertaken on a few Cuu Long sections and suggest that a 100 kyr cyclicity may also be present in this basin, hidden behind the 406 kyr cycles (Fig. 14) but is of too high resolution to be evaluated biostratigraphically using cuttings samples.

A proposed correlation of the 36 depositional cycles seen in Cuu Long Basin with the 406 kyr cycles of Paalike *et al.* (2006), and Westehold *et al.* (2014) is presented in Fig. 15. The succession is tied firstly on the position of the base lower Miocene, which is interpreted to coincide with the Sequence 30 sequence boundary, occurring a short distance below the base of *Florschuetzia levipoli* at 21.6 Ma at the base of Sequence 31, and the evolutionary appearance of *Ceratopteris* spores (form taxon *Magnastriatites howardi*) within Sequence 6.

#### **Insert Fig 14 approx here Cyclogram**

#### **Insert Fig 15 approx here Chronostrat chart**



## 8. Relationship with seismic data

The BI.1, BI.2, C, D and E seismic markers were initially compared to the succession of proposed palynological zones, and where appropriate, adjustments were made either with the position of palynological zone boundaries or with seismic picks where there was any ambiguity in placement. This approach was then followed with respect to the high-resolution depositional sequences for each well pair across the basin. This resulted in a very close agreement between interpretations using biostratigraphy and seismic (Fig. 16). Regional seismic picks could be shown either to relate to maximum flooding surfaces, or to sequence boundaries. Seismic picks E and D clearly relate to unconformities. Seismic pick C, on the other hand ties to the Sequence 22 mfs where the sequence was well developed, and the mfs distinctly separate from the overlying sequence boundary, but where the Sequence 22 highstand was thin, the pick tied to the overlying sequence boundary. Seismic pick BI.1 also ties closely to a flooding surface (Sequence 29), with the BI.2 seismic pick tying to the Sequence 31 mfs (Fig 11).

In several instances, especially in marginal sub-basins and across major faults, the depositional cycle succession identified major seismic mis-ties, that have since been corrected.

Insert Fig 16 approx here (seismic corr)

## 9. Implications with respect to regional geology and sequence stratigraphy

The differences in opinion regarding the tectonic history of the Cuu Long Palaeogene succession relate in part to a lack of understanding of the detailed chronostratigraphy of the basin (e.g. Lee *et al.*, 2003; Hung and Le, 2004; Swiecicki and Maynard, 2009; Schmidt *et al.*, 2019). This study suggests that the Oligocene-Miocene boundary should be placed at the top of the Lower Bach Ho Formation, at seismic horizon BI.1, rather than the top of the Upper Tra Tan Formation at seismic horizon C since placement at the top of the Tra Tan Formation requires inappropriately high sedimentation rates for the Lower Bach Ho Formation.

The Oligocene to upper Eocene stratigraphic succession in the basin is characterised by high frequency, equi-thickness depositional cycles reflected in palynomorph assemblages that are climate driven, suggesting correlation to astronomically driven Milankovich eccentricity cycles. There are several unconformities in the succession, but it is thought that by using a database of many wells spread widely across the basin, the entire Palaeogene succession has been captured. Paalike *et al.* (2006) showed that 406 kyr eccentricity cycles form the 'heartbeat of the Oligocene' climate system and it is suggested that it is this cyclicity that has driven the cyclical deposition seen in the Cuu Long Basin. This is suggested by counting sequences between dated horizons. Positioning the top of the Oligocene at the top of Sequence 29, on the highest occurrence of the Oligocene index palynomorph *Cicatricosisporites dorogensis*, which occurs a little way below the evolutionary appearance of *Florschuetzia levipoli* (21.5 Ma), and using an intra late Eocene datum (the lowest consistent occurrence of *Ceratopteris* spores (form taxon *Magnastriatites howardi*), evolutionary appearance at 35 Ma) at the base of Sequence 6, the intervening 30 cycles would

each represent 396 kyr, strongly supporting correlation to 406 kyr Milankovich cycles. The possibility needs to be raised that these cycles may be interfered with by higher frequency (106 kyr) cyclicity, noted in some Chinese lacustrine successions (Li *et al.* 2012), but it is considered that by using many wells, and by systematically cross-checking correlations between adjacent wells by reference to seismic, such interference is unlikely.

Astronomically driven climate cycles of the same cyclicity extending from the Paleocene to Oligocene have recently been demonstrated for the Bohai Bay Basin in northern China based on spectral analysis of gamma logs from basinal wells (Liu *et al.*, 2018). Similar cyclicity is widespread in Vietnamese Oligocene successions, also noted in Song Hong Basin, in North Vietnam (VPI unpublished data). An upper Oligocene well section from Bach Long Vi Island marginal to the Song Hong Basin has been continuously cored (Petersen *et al.*, 2014) and shows high frequency lithological cyclicity throughout which is in the process of being evaluated (VPI and GEUS unpublished). Detailed time-series analysis of this core, the only long core from any of the Vietnamese Oligocene basins, combined with closely spaced palynological sampling should further confirm the different cyclicities which have affected lacustrine deposition in these basins.

The detailed chronostratigraphy allows judgments to be made on the nature of the 3<sup>rd</sup> and 4<sup>th</sup> order depositional sequences, the timing of basin formation and the timing of the major unconformities that are present. Also, it is possible to suggest direct correlations to adjacent basins.

### **9.1. Two types of depositional sequence**

The Oligocene is characterised by two types of depositional sequence (Fig. 17): repetitive, short-lived climate-driven packages, termed 'Sequences' but perhaps better visualised as parasequences, and longer-term packages, each comprising a succession of parasequences separated by unconformities, and which tie to the main seismic divisions within the Oligocene and upper Eocene. These are best visualised as 3<sup>rd</sup> order sequences, with the parasequences forming 4<sup>th</sup> order sequences.

A similar approach proposed here for the Cuu Long Basin applied to continental margin successions with clearly defined systems tracts may greatly clarify the understanding of the real controls on depositional sequences and clarify the nature of the basic controls that drive sequence stratigraphy globally.

**Insert Fig 17 approx here Chronostrat summary**

### **9.2. Nature and timing of tectonic events**

Basin initiation probably began sometime before 37 Ma, within the middle Eocene, approximately at the same time as the initiation of rifting along the Chinese margin that preceded the opening of the South China Sea (Larsen *et al.*, 2018). The onset of basin formation closely follows other basins on the Sunda Shelf, such as the West Natuna and Malay Basin (Morley, 2014) as well as the Nam Con Son and basins to the south of Cuu Long. Basin initiation was therefore

much later than in the basins of Eastern Kalimantan, such as the Kutai and Tarakan, which contain a distinct Middle Eocene succession in the synrift, with basin initiation close to the base of the Middle Eocene (Morley, 2014, van Gorsel *et al.*, 2015).

The Cuu Long succession then underwent three main phases of renewed tectonic adjustment, resulting in unconformities after 33.4 Ma, 29.8 Ma and 27.4 Ma and 23 Ma (Fig. 16). A summary of the ages of formational boundaries and seismic picks are presented in Table 3.

**Insert Table 3 approx here**

### **9.3. Palynological and sequence biostratigraphic correlation with West Natuna Basin**

The West Natuna basin is the only area from South East Asia outside Cuu Long which has already been evaluated for high frequency depositional sequences (Morley *et al.*, 2007), which are also thought to reflect 406 kyr eccentricity cycles (Morley, 2012). The possibility needs to be brought to attention that this may reflect similar depositional controls in the two basins, as climate trends are broadly similar, with the West Natuna climate becoming increasingly seasonally dry toward the latest Oligocene (Morley, 2012). However, there are clear differences; whereas the Cuu Long succession remained essentially freshwater throughout the Upper Tra Tan and Lower Bach Ho, with water bodies rich in freshwater algae, the West Natuna Basin is characterised by floods of the brackish water foraminifer *Miliammina*, interfingering with algal maxima, indicating repeated intermittent brackish incursions through the Udang and Barat Formations (Morley *et al.*, 2007).

It is thought that the change from less seasonally dry (supporting tall deciduous forests) to more seasonally dry climates supporting pine woodlands in the mid Lower Bach Ho Formation corresponds to a change to seasonally drier climates in the mid Udang Formation (Morley, 2012). By substituting the Cuu Long Sequence numbers to West Natuna, from the top Barat Formation downward, the top of the Tra Tan Formation, characterised by widespread lacustrine deposition, corresponds closely to the top of the lacustrine Gabus Formation in West Natuna (Fig. 18).

**Insert Fig 18 approx here Corr to W Natuna**

### **9.4. Comparison between Cuu Long and other nearby basins**

Comparison with the chronostratigraphic framework for Malay Basin, Penyu and West Natuna Basins (Fig. 1A), based on the stratigraphic chart of the basins of Malaysia (Boyce *et al.*, 2006) which has been rescaled to comply with Ogg *et al.* (2012), shows significant correspondences with respect to the position of unconformities (Fig. 19). The upper part of the Lower Bach Ho Formation above Sequence 26 may tie with Malay Basin seismic Group K and the Barat Formation in West Natuna. The lower part of the Lower Bach Ho would then correlate with Malay Basin Seismic Group L and the Udang Formation in West Natuna. The upper part of the Upper Tra Tan Formation equates with the upper part of seismic Group M in the Malay Basin, with the Cuu Long C seismic pick correlating with top Gabus in West Natuna.

The correlation suggests that the base of the Upper Tra Tan Formation may tie with the lower part of seismic Group M in Malay Basin and the Belut Formation in West Natuna, and if this was

the case, the Benua Formation in West Natuna would correlate with the Lower Tra Tan Formation in Cuu Long, and the Lama Formation in West Natuna Basin would correlate with the Tra Cu Formation in Cuu Long. The above correlations are based on inference only, with supporting biostratigraphic analyses only for the Udang and Gabus Formations in West Natuna by Morley *et al.* (2007). Clearly additional studies on the Malay and West Natuna basins are needed to confirm these correlations.

With respect to the Bohai Bay Basin (Liu *et al.*, 2018), the combined Dongying Formation and Members 1 and 2 of the Shahejie Formation tie to the combined Tra Cu, Tra Tan and Lower Bach Ho Formations. However, there seem to be few obvious intra Oligocene ties.

**Insert Fig 19 approx here corr to adjacent basins**

The Nam Con Son Basin has previously been evaluated by Matthews *et al.* (1997), Lee *et al.* (2003), Swiecicki and Maynard (2009) and Morley *et al.* (2011) and Dung *et al.* (2018), but there is insufficient data to make suggestions as to how the Palaeogene succession might correlate with the Cuu Long Basin.

## 10. Conclusions

A comprehensive sequence biostratigraphic evaluation of the Cuu Long Basin Palaeogene succession has provided an accurate time framework based on the identification of 36 transgressive-regressive depositional cycles. These are most likely climate-driven and are correlated to the 406 kyr 'heartbeat of the Oligocene' eccentricity cycles of Paalike *et al.* (2006).

This calibration allows precise age interpretations for sequence boundaries, and the timing of tectonic events that have affected the basin. Whereas the high-resolution cycles, which may be viewed as parasequences, or 4<sup>th</sup> order sequences, are entirely climate-driven, they form the component parts of five 3<sup>rd</sup> order sequences which are readily reflected by seismic and are clearly driven by tectonics alone. The study therefore demonstrates that it is indeed possible to differentiate eustatic from tectonic subsidence, contrary to the opinion of many sequence stratigraphers. A similar approach applied to continental margin successions, with clearly defined systems tracts, will greatly clarify the understanding of the real controls on depositional sequences.

Traditionally, the Oligocene-Miocene boundary has been placed at the top of the Tra Tan Formation. In this study, it is considered that a much more realistic position for the Oligocene-Miocene boundary is at the top of the lower Bach Ho Formation.

Astronomically-driven eccentricity cycles appear to have affected deposition from the West Natuna Basin at 5°N to the Bohai Bay Basin at 38°N and it is suggested that 406 kyr climate-driven cyclicity is a general feature of mid Cenozoic basins along the East Asian seaboard.

It is suggested that by applying the methods used here to the other basins of the Sunda Shelf and offshore Vietnam will greatly improve our understanding of the Eocene-Oligocene stratigraphy and tectonic development of the basins across the South East Asian region.

## Acknowledgments

The palynological and micropalaeontological analyses were undertaken by biostratigraphers of the VPI laboratories in Ho Chi Minh City. Tony Swiecicki read the paper and made some useful suggestions. The authors are very grateful to Murphy Oil Corporation, Vietnam Petroleum Institute and PetroVietnam for permission to publish this paper. The original work was funded by Murphy Oil Corporation and the work program that eventually led to the preparation of this paper was initiated by Pedro Restrepo-Pace. We are very grateful to Michael Fyhn and two anonymous reviewers for suggestions that greatly clarified the text.

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# Appendix 1 Palynomorph source taxon ecology

## Vascular plants

Taxon (extant)	Taxon (dispersed fossil)	Ecology/comments
<i>Acrostichum</i>		Today ferns of disturbed mangroves but in Cuu Long Oligocene ferns of disturbed fluvial settings
<i>Alnus</i>	<i>Alnipollenites</i> spp.	Temperate and montane trees
<i>Arenga</i>	<i>Arengapollenites achinatus</i>	Palm tree often found in freshwater swamps
<i>Barringtonia</i>	<i>Marginipollis concinnus</i>	Tree of coastal forests and lake margin swamps. In Cuu Long mainly thought to be derived from seasonally inundated freshwater swamp forest, as seen in around present day Tonle Sap
<i>Brownlowia</i> type	<i>Discoidites</i> spp.	Trees of riverine and brackish swamps
<i>Calamus</i> type	<i>Dicolpopollis</i> spp.	Rattans, common elements of tropical evergreen rain forest, but also in some freshwater swamps
<i>Carya</i>	<i>Caryapollenites</i> spp.	Temperate and montane trees
<i>Ceratopteris</i>	<i>Magnastriatites howardi</i>	Aquatic fern, sometimes rooted, sometimes floating, probably grows in floating mats, as marshes, and also within swamp forest
Extinct Schizaeaceae	<i>Cicatricosisporites dorogensis</i>	Extinct fern, probably of well drained habitats
Dipterocarpaceae		Most common rain forest tree family of South East Asia, typically form more than 50% of forest biomass, produces very little pollen in perhumid forests, but probably bigger producer in seasonally dry forests
Sonneratioid	<i>Florschuetzia trilobata</i>	Precursor to <i>Sonneratia caseolaris</i> , probably grew in lake margin swamps and backmangrove settings
Sonneratioid	<i>Florschuetzia semilobata</i>	Precursor to <i>Sonneratia caseolaris</i> , probably grew in backmangrove settings

Poaceae	<i>Monoporites annulatus</i>	Herbs of seasonally dry forest and savanna
<i>Lagerstroemia</i>		Precursor of sonneratioids, common tree of semi-evergreen and tall deciduous forests
Cf. <i>Livistona</i>		Palm tree, typical of freshwater swamps
<i>Nypa</i>	<i>Spinizonocolpites echinatus</i>	Backmangrove palm, grows in slightly brackish or fresh water but mostly within the reach of tidal influence
<i>Oncosperma</i>	<i>Racemonocolpites hians</i>	Palm of backmangrove/coastal settings and hill forest
<i>Riccia</i> type	<i>Lycopodiumsporites neogenicus</i> , <i>Riccia</i> spores	Probably from mosses, which grew on seasonally inundated marshes
<i>Pinus</i>	<i>Pinuspollenites</i> spp.	Coniferous tree of both lowlands and mountains, but in Cuu Long area probably mainly derived from seasonally dry Pine/dipterocarp savanna
<i>Pterocarya</i>	<i>Pterocaryapollenites</i> spp.	Temperate and montane deciduous trees. Will only grow in areas with winter frosts
<i>Picea</i>	<i>Piceapollenites</i> spp.	Montane/temperate trees. Will only grow in areas with winter frosts, mainly on cool foggy mountain tops
<i>Pteris</i>		Terrestrial ferns
<i>Sonneratia caseolaris</i>	<i>Florschuetzia levipoli</i>	Backmangrove tree in brackish or freshwater intertidal settings
<i>Stenochlaena palustris</i>	<i>Verrucatosporites usmensis</i>	Climbing ferns, common in swamp forest and open marsh vegetation
<i>Tilia</i>	<i>Tiliapollenites</i> spp.	Montane/temperate trees, will only grow in areas with winter frosts
Sonneratioid	<i>Trilobapollis</i> spp.	<i>Sonneratia</i> precursors, probably grew in lake margin swamps
<i>Tsuga</i>	<i>Tsugaepollenites</i> spp.	Montane/temperate trees. Will grow only in areas with winter frosts, in marginal tropics on cool mountain tops
<i>Algae</i>		

	<i>Bosedinia</i> spp.	Resting cysts of extinct freshwater dinocysts lineage, probably from deepest/most distal lakes
<i>Botryococcus</i> spp.		Freshwater alga, from shallow/proximal lakes
<i>Pediastrum</i> spp.		Freshwater alga from intermediate to deeper/more distal lakes

Appendix 1 Taxonomic nomenclature of pollen, spores and algal palynomorphs mentioned in the text and notes on the ecology of their source taxa.

### Palynomorph groupings

The palynomorph groupings are as follows:

#### a) Mangrove and lake margin pollen/spores

*Acrostichum* – ferns of disturbed/open areas in present day mangrove/ backmangrove swamps but in Oligocene mainly surrounded freshwater lakes

*Backmangrove and lake margin* – diverse group of swamp forest and facultative mangroves growing behind true mangroves or bordering freshwater lakes. Typical examples in Cuu Long are: *Florschuetzia trilobata*, *Brownlowia* type, *Trilobapollis* spp. Their interpretation is complex in the Cuu Long Basin

*Nypa* – mangrove palm, grows in freshwater intertidal and low salinity settings, gregarious on fluvially dominated deltas, such as Mahakam

*Rhizophoraceae* – true mangroves, typically growing adjacent to sea, prefer salinities of 15-30‰

#### b) Other pollen

This is essentially derived from freshwater swamp and upland *terra firma* settings behind/upstream from the mangrove or lake margin zone as follows:

*Coastal and lake margin* – occurring on beach ridges and barrier bars – in Cuu Long many probably occurred in lake-margin settings, especially *Barringtonia*

*Rain forest* – mainly from rain forests and freshwater alluvial swamps, indicating a perhumid climate. Dipterocarpaceae and *Calamus* type fall into this group

*Peatswamp* – pollen from plants which grow on peats but may not be restricted to them

*Riparian* – derived from plants which mainly grow along lowland rivers. In Cuu Long may also have occurred on lake-margin swamps

*Seasonal* – includes taxa of grasslands and open forest, such as the grasses (Poaceae) and herbs of open vegetation. *Pinus* is included in this group

*Temperate gymnosperms* – Gymnosperms that are frost-tolerant and currently restricted to seasonal climate montane settings on the periphery of the tropical zone or in temperate climates. *Abies*, *Picea* and *Tsuga* are the main examples (Morley 2018)

*Temperate angiosperms* that are currently restricted to montane settings in seasonal tropical climates. This group includes *Alnus*, *Carya*, *Juglans*, *Pterocarya* and *Tilia*.

c) *Pteridophyte spores, excluding Acrostichum*

*Terrestrial wet ferns* of freshwater swamps, especially spores of *Ceratopteris* and *Osmunda*

*Terrestrial dry ferns* of mainly dryland areas, especially *Pteris*

*Climbing ferns* epiphytic and climbing ferns such as *Stenochlaena* and *Lygodium*

*Other ferns (Undifferentiated)* Spores which cannot be identified, are grouped into broad morphological groups, monolete, and trilete.

d) *Algae*

Grouped as follows:

*Algae* – freshwater dinocysts of the *Bosedinia* group and colonial freshwater algae such as *Pediastrum* spp. and *Botryococcus* spp.

*Marine dinocysts* – typically marine but sometimes occurring in lacustrine settings.

Figure captions

Fig. 1. A. Cuu Long Basin location, and position of other basins mentioned in the text. B. Well locations and basin outline. Red – key wells, grey – other wells, seismic line in Fig. 16 in red. Other lines connect well pairs for which depositional cycles have been individually cross checked against seismic.

Fig. 2. Previous and revised stratigraphic profile for Cuu Long Basin. Previous chronostratigraphy follows Hiep (2017). The regional seismic section across the basin shows the initial rift infill and subsequent inversion and regional subsidence phases.

Fig. 3. Presentation of palynomorph assemblage groupings. Hinterland pollen is presented in terms of the pollen sum ‘total hinterland pollen’; all other groupings presented ‘outside’ the sum (sensu Faegri and Iversen 1964). Hinterland pollen (%) provides information on climate change, hinterland pollen and fern spores provide the main events useful for regional correlation; lake margin pollen, hinterland pollen recorded per slide, fern spores and algae provide criteria for interpreting depositional environments and the identification of depositional cycles. Profile thickness 560m.

Fig. 4. Characterisation of lacustrine facies using palynology as applied in this study based on Morley and Morley (2013).

Fig. 5. Well A, Example of depositional cycles reflected by different parameters. Lake margin pollen and fern spores plotted as % ‘terra firma’ pollen. Note that lake margin pollen and fern

spores increase as algal palynomorphs decrease, indicating a shallowing lake; for algal palynomorphs, using % total palynomorphs allows lacustrine facies to be differentiated from overbank (section 3); 'total algal palynomorphs recorded per slide' identify main periods of flood, but when algal palynomorphs are plotted as % 'terra firma' pollen, the depositional cycles are revealed even when palynomorph recovery is low. Section thickness, 1600 m.

Fig. 6. Characterisation of palynological zones in western Cuu Long Basin for seismic groups BI.1, C and D. Gamma log to left, horizontal scale 0-140 api units; *Arenga*, *Barringtonia*, *Brownlowia* type, *Calamus* type, Dipterocarpaceae, *Florschuetzia semilobata*, *Pinus*, *Riccia* type, *Verrutricolporites pachydermus* plotted as number of specimens recorded per sample, horizontal scale 0-50 specimens (0-25 for narrow columns), cf. *Livistona* plotted as number of specimens per sample, horizontal scale 0-100 specimens; *S. palustris* plotted as % hinterland pollen, scale 0-50%. Well B, section thickness, 1836m, Well C, section thickness 2004 m, Well E, section thickness 165 m.

Fig. 7. Characterisation of palynological zones in eastern Cuu Long Basin for seismic groups D and E. Gamma log to left, horizontal scale 0-140 api units; *Brownlowia* type, *Calamus* type, Dipterocarpaceae, *Pinus*, *Riccia* type, temperate angiosperms and *Verrutricolporites pachydermus* plotted as number of specimens recorded per sample, horizontal scale 0-50 specimens (0-25 for narrow columns), cf. *Livistona* plotted as number of specimens per sample, horizontal scale 0-100 specimens; *S. palustris* plotted as % hinterland pollen, scale 0-50%. Well J, section thickness 840 m, Well K, section thickness 1090 m.

Fig 8. Schematic summary of Cuu Long palynological zones, and relationship to PR zones from the Malay Basin (Yakzan *et al.* 1996, Morley *et al.* 2015) and the E zones proposed for the Palaeogene of Indonesia in van Gorsel *et al.* (2014) and Witts *et al.* (2012). The dotted lines through zone CLO-9C reflect a widespread interval with low palynomorph recovery in many wells. The thickness changes for taxa indicate the events that are useful for correlation only. The widths of these reflects relative change rather than actual abundance.

Fig. 9. Characterisation of depositional cycles in selected key western Cuu Long Basin wells. Most cycles are characterised by algal palynomorph maxima. In proximal settings, algae are of limited occurrence and flood events are reflected by maxima of *Ceratopteris* spores (see Fig 11, Sequence 30, Fig 12 Sequence 26, 28).

Fig. 10. Characterisation of depositional cycles in selected eastern Cuu Long Basin wells. Most cycles are characterised by algal palynomorph maxima.

Fig. 11. Well E, climate cyclicity within Sequences 29-31 (thickness 165 m), Three cycles of climate change are reflected in changes from dominant seasonal climate elements (mainly *Pinus*) at the beginning of a depositional sequence to dominance of rain forest elements at the end of the sequence. The relationship to the pattern of seismic reflectors, positions of sequence boundaries and maximum flooding events is shown to the left. Interpreted climate trends are shown to the right, by reference to the vegetation types of Ashton (2014).

Fig. 12. Well C. Climate cyclicity within Sequences 20 to 29. Section thickness 860 m.

Fig. 13. Comparison of sedimentation rates based on different cyclicities. The evolutionary appearance of *Ceratopteris* spores (*Magnastriatites howardi*) is based on Witts *et al.* 2012.

Fig. 14. Well D, Fluctuations from Cyclog Inpefa analysis (Nio *et al.* 2005) suggest possible 100 kyr cyclicity in addition to suggested 406 kyr cyclicity suggested from palynomorph assemblages.

Fig. 15. Proposed chronostratigraphy and correlation of depositional sequences with 406 kyr cycles of Paalike *et al.* (2006), providing an age framework for the Cuu Long depositional cycles. RMCD = revised metres composite depth (from Paalike *et al.* 2006).

Fig 16. Tying depositional cycles to seismic by converting biostratigraphic sample depth data to Two Way Traveltime and pasting against seismic profile, Line X. The sawtooth diagrams show abundance of freshwater algae presented as a percentage of total hinterland pollen. The horizontal scale is 0-5000%. See Fig. 1 for location. This process, undertaken for all adjacent well pairs shown in Fig. 1, removes most correlative errors due to insufficient sample spacing, and also clarifies the regional character of sequence boundaries.

Fig 17. Chronostratigraphic chart, showing age, formations, high frequency depositional sequences and age of their sequence boundaries, tectonically driven sequences, and seismic packages. 'Lake margin swamp' in Upper Bach Ho Formation includes some mangroves. A-K, key wells used in this study; thick lines, reference sections shown in Figs 9 and 10; thin lines, other key wells and full extent of wells that contain reference sections.

Fig. 18. Correlation with North Belut-5 well, drilled in the West Natuna Basin (Morley *et al.* 2007). Foraminiferal analysis was undertaken to the base of the Barat Formation, and the cyclicity has been projected to the top of the Barat Formation (top Oligocene) using the gamma log. With these additional cycles, the Cuu Long Sequences have been substituted for the cycles numbered in Morley *et al.* (2007). C = cored interval, NB = North Belut depositional sequences according to Morley *et al.* (2007).

Fig. 19. Comparison with Malay, Penyu, West Natuna Basins (from Boyce *et al.* 2007) and Bohai Bay Bay Basin (Lui *et al.* 2018). The Malaysian chronostratigraphic chart has been rescaled to a linear scale and also adjusted to comply with the current ICS timescale of Ogg *et al.* (2016). For Bohai Bay Basin, Ed = Donying Formation, ES<sup>1</sup>, ES<sup>2</sup> and ES<sup>3</sup> = 1<sup>st</sup> 2<sup>nd</sup> and 3<sup>rd</sup> Members of the Shahejie Formation.

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Tables

Zone/Subzone	Palynological characteristics
Zone CLM-2	Based on the lowest stratigraphic occurrence of consistent <i>Florschuetzia levipoli</i> , and an acme of <i>Arenga</i> pollen, the base of which generally is its stratigraphically deepest occurrence, and common <i>F. trilobata</i> . This zone corresponds to the lower part of zone PR9a of Yakzan <i>et al.</i> (1996).
Zone CLM-1	This zone is positioned at the deepest consistent occurrence of <i>Florschuetzia semilobata</i> , occurring without <i>F. levipoli</i> , and the common occurrence of <i>Dicolpopollis</i> spp. and 'cf <i>Livistona</i> ' pollen. The zone corresponds to zone PR8 of Yakzan <i>et al.</i> (1996).
Subzone CLO-9C	An interval subzone for the succession below the deepest occurrence of <i>Florschuetzia semilobata</i> , and above the highest occurrence of common <i>Barringtonia</i> pollen that marks the top of CLO-9B. The top of the zone also approximately corresponds to the youngest occurrence of <i>Cicatricosisporites dorogensis</i> and to the youngest occurrence of common <i>Bosedinia</i> spp.
Subzone CLO-9B	The top of this subzone is based on a good regional event with a sudden down-section increase of <i>Barringtonia</i> pollen and the regular occurrence of <i>Verrutricolporites pachydermus</i> and common <i>Cicatricosisporites dorogensis</i> .
Subzone CLO-9A	This subzone is based on a sudden down-section increase of <i>Brownlowia</i> pollen and the common occurrence of <i>Verrutricolporites pachydermus</i> . The event is 'sequence driven' and can be easily recognised if its position relative to top CLO-9B is considered.
Zone CLO-8	This zone is indicated from the increased representation of <i>Dicolpopollis</i> spp. across the region, probably reflecting a change to a wetter climate down-section.
Zone CLO-7	The zone is based on a down-section reduction in representation of <i>Dicolpopollis</i> spp. and an increase in <i>Pinus</i> pollen, suggesting a more seasonal climate than for zone CLO-8.
Subzone CLO-6b	This subzone is based on the increased occurrence down-section of regular <i>Riccia</i> type spores and also common Dipterocarpaceae pollen, coupled with a further increase of <i>Pinus</i> pollen. <i>Riccia</i> type spores sometimes occur as scattered specimens above CLO-6b, but these are rare.
Subzone CLO-6a	Subzone CLO-6a is characterised by a distinct further down-section increase in abundance of <i>Riccia</i> type spores, and the increased diversity of this spore group coupled with decreased <i>Pinus</i> pollen.
Zone CLO-5	This zone is characterised by a down-section increase of cf. <i>Livistona</i> pollen. This pollen type is often extremely common within the zone
Zone CLO-4	This zone is characterised by high percentages of temperate angiosperm pollen (mainly Fagaceae). The stratigraphically deepest <i>in situ</i> specimens of <i>Ceratopteris</i> spores occur within the lower part of the zone.

Table 1. Definition of palynological zones.

Forest type	Dry season length	Decid/ evergr
Lowland evergreen rain forest/ Mixed dipterocarp forest	0-2 months	Evergreen
Seasonal evergreen dipterocarp forests	3-5 months	Mixed
Semi-evergreen forests	6-7 months	
Tall (moist) deciduous forests	8-9 months	Deciduous
Short (dry) deciduous forests		
Savanna	7-10 months	

Table 2. Classification of vegetation types of Indochina in terms of climate (from Ashton 2014).

Event	Age (Ma)
Top Upper Bach Ho Formation	20.5
Bl.2 seismic pick	20.7
Top of Lower Bach Ho Formation	23.0
Bl.1 seismic pick	23.2
Top of Upper Tra Tan Formation	27.4
C Seismic pick	27.6
Top of Lower Tra Tan Formation	29.8
D Seismic pick	29.8
Top of Tra Cu Formation	33.4
E Seismic pick	33.4
G Seismic pick	36.6
Base of succession	~39 or slightly older

Table 3. Ages of formational boundaries and seismic picks in Cuu Long Basin based on this study.

**Highlights**

- The Cuu Long Palaeogene is characterised by 36 approximately equi-thickness depositional cycles
- These correlate to 406 kyr eccentricity driven 'heartbeat of the Oligocene' climate cycles
- The cycles group into packages which form 3rd-order tectonically-driven sequences
- Correlation to the stable isotope record provides an accurate date of each cycle and sequence boundary.

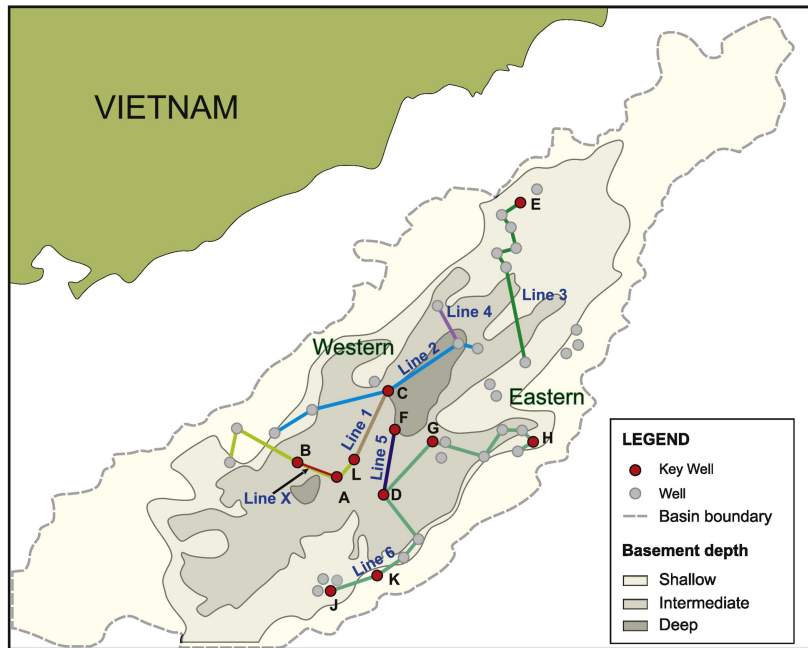
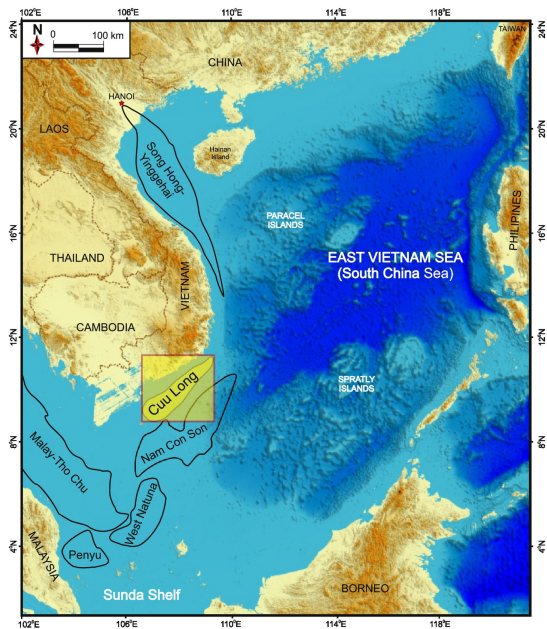


Figure 1

Age		Formation	Lithology	Seismic Hor. and Group
This study	Previous			
Pliocene-Quaternary	Pliocene-Quaternary	Bien Dong	[Conglomerate symbol]	Hor. B.III
Miocene	Upper	Dong Nai	[Sandstone symbol]	Hor. B.II
	Lr. - M.		[Sandstone symbol]	
	Middle	Con Son	[Sandstone symbol]	Hor. B.I.2
	Lower		'Rotalia' bed	Gr. B.I.2
Oligocene	Upper	Bach Ho	[Sandstone symbol]	Hor. B.I.1
	Lower		[Sandstone symbol]	Gr. B.I.1
	Upper	Tra Tan	[Shale symbol]	Gr. C
	Lower		[Shale symbol]	Gr. D
Eocene	Upper	Tra Cu	[Sandstone symbol]	Hor. E
			[Sandstone symbol]	Gr. E
	M - ?U	Ca Coi	[Conglomerate symbol]	Hor. F/G
Pre-Tertiary			[Basement symbol]	Basement

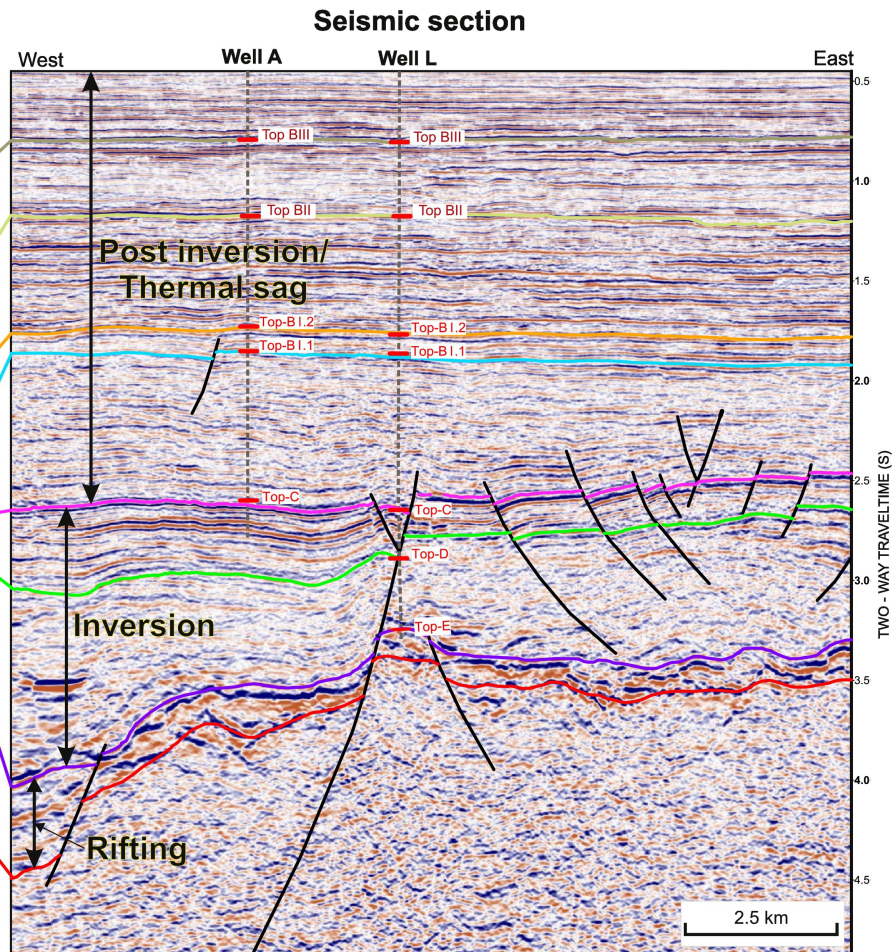


Figure 2

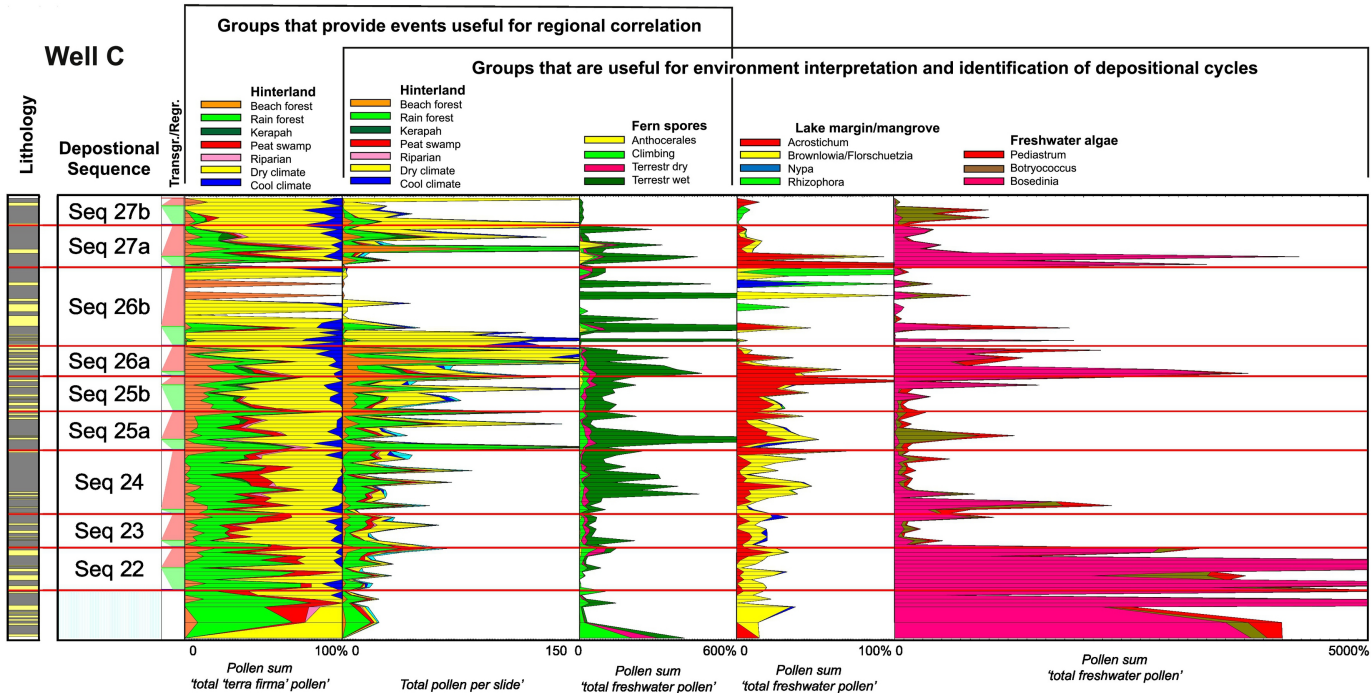


Figure 3

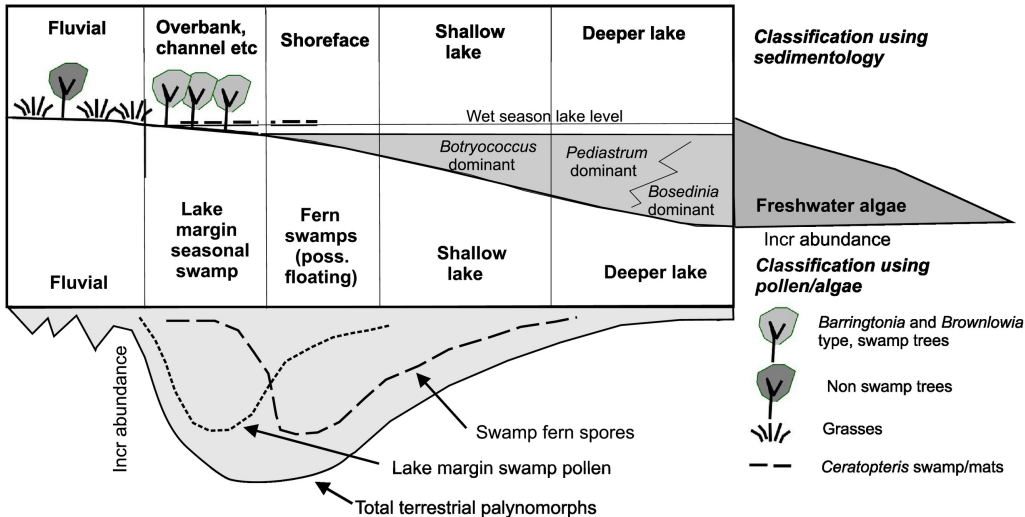


Figure 4



# Well A

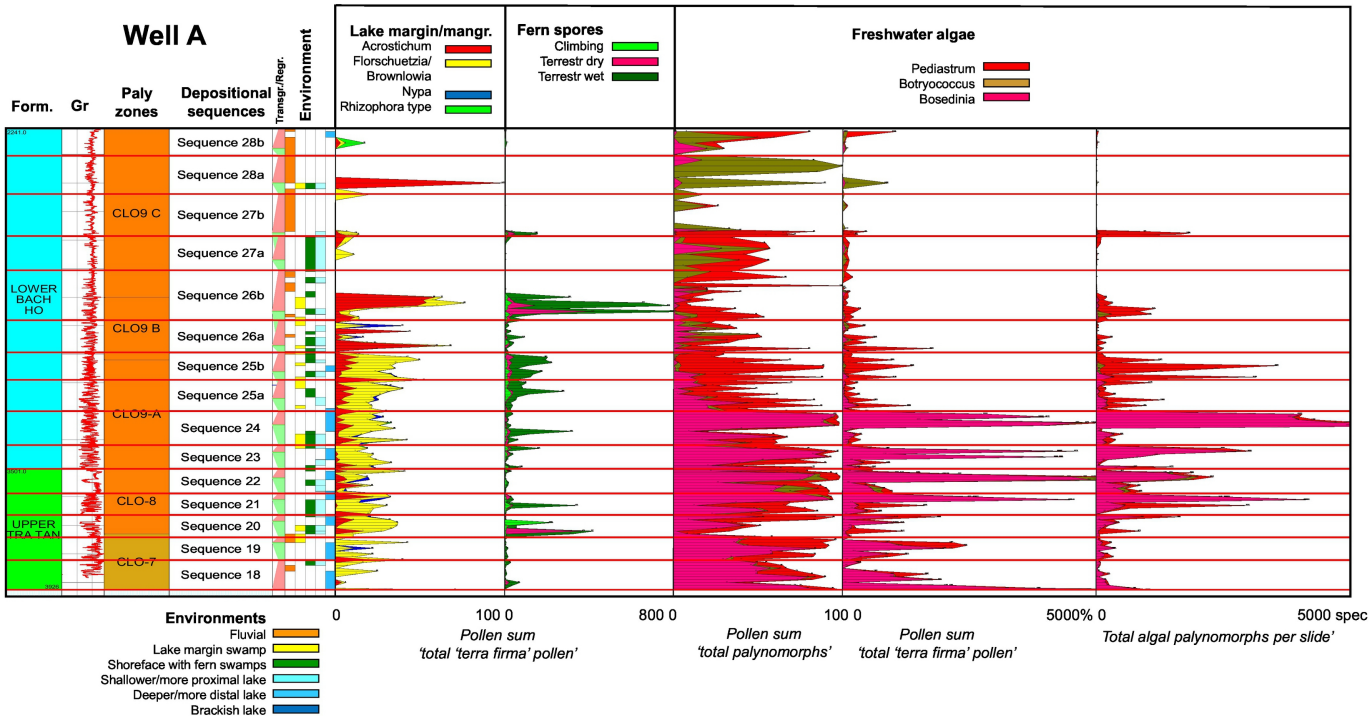


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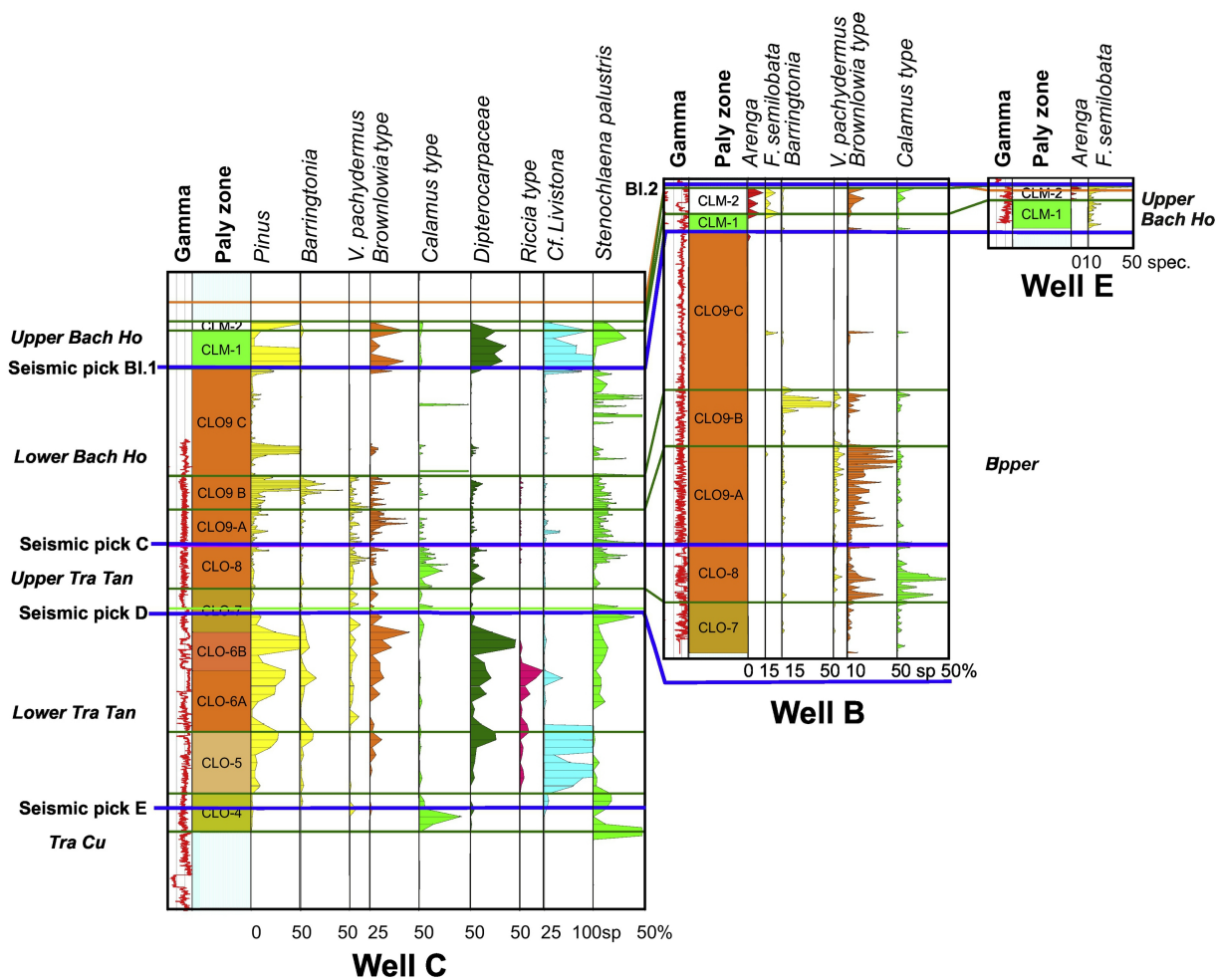


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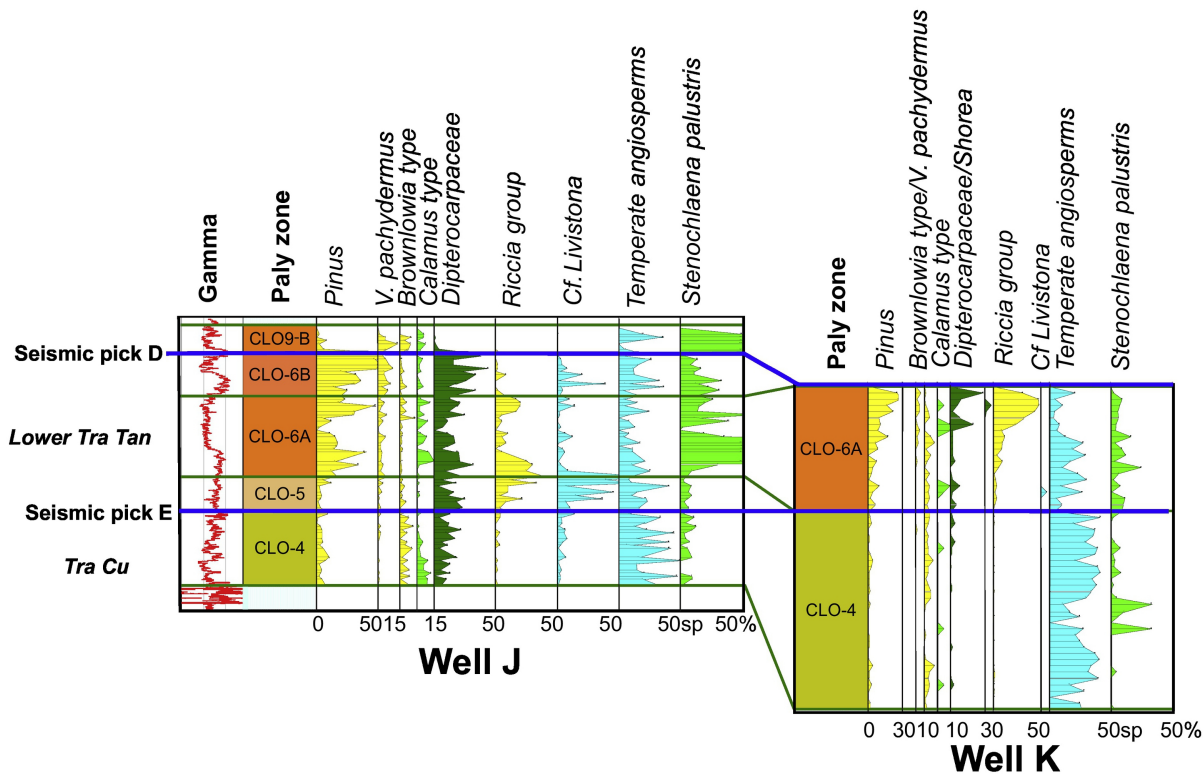


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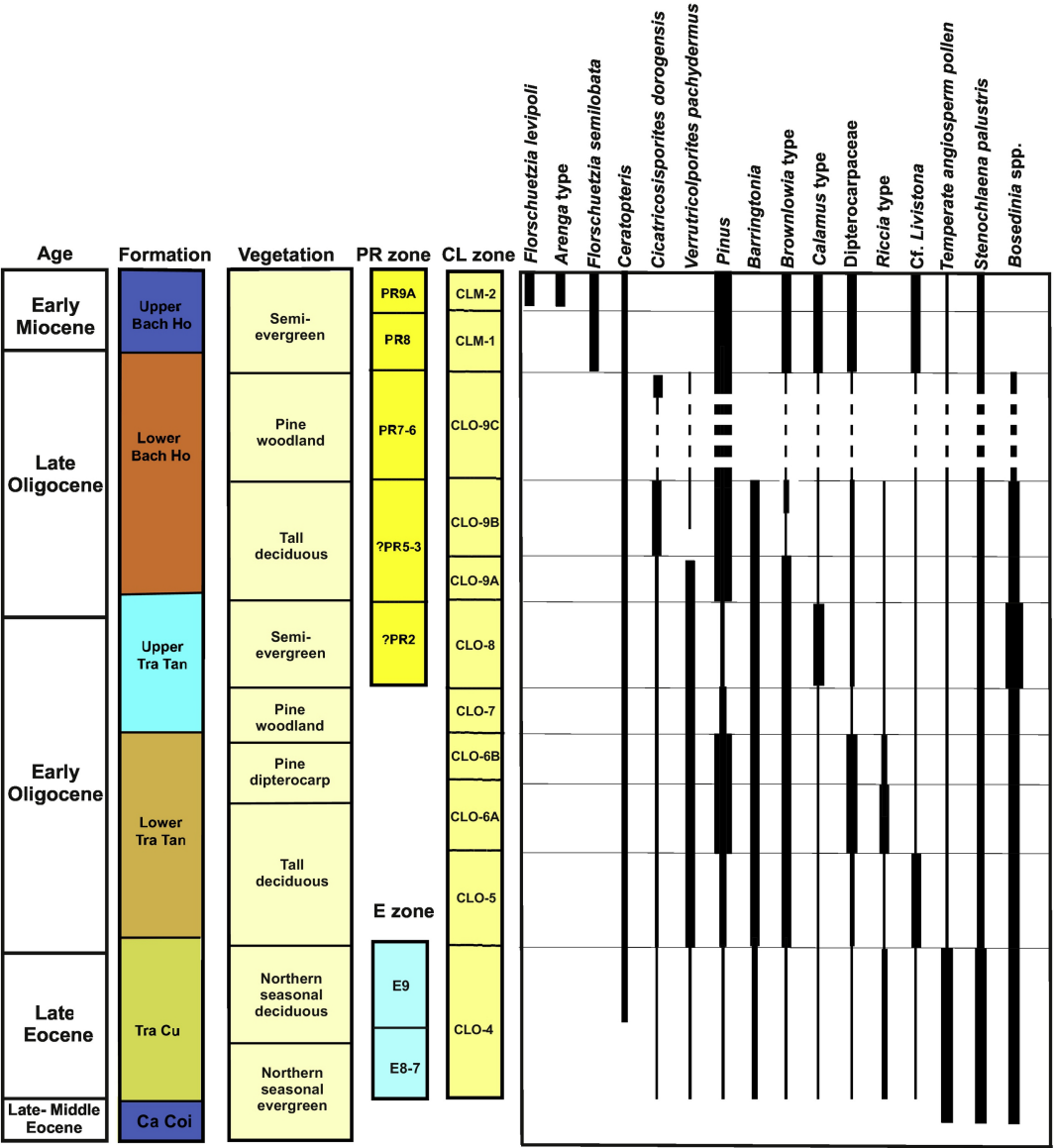


Figure 8

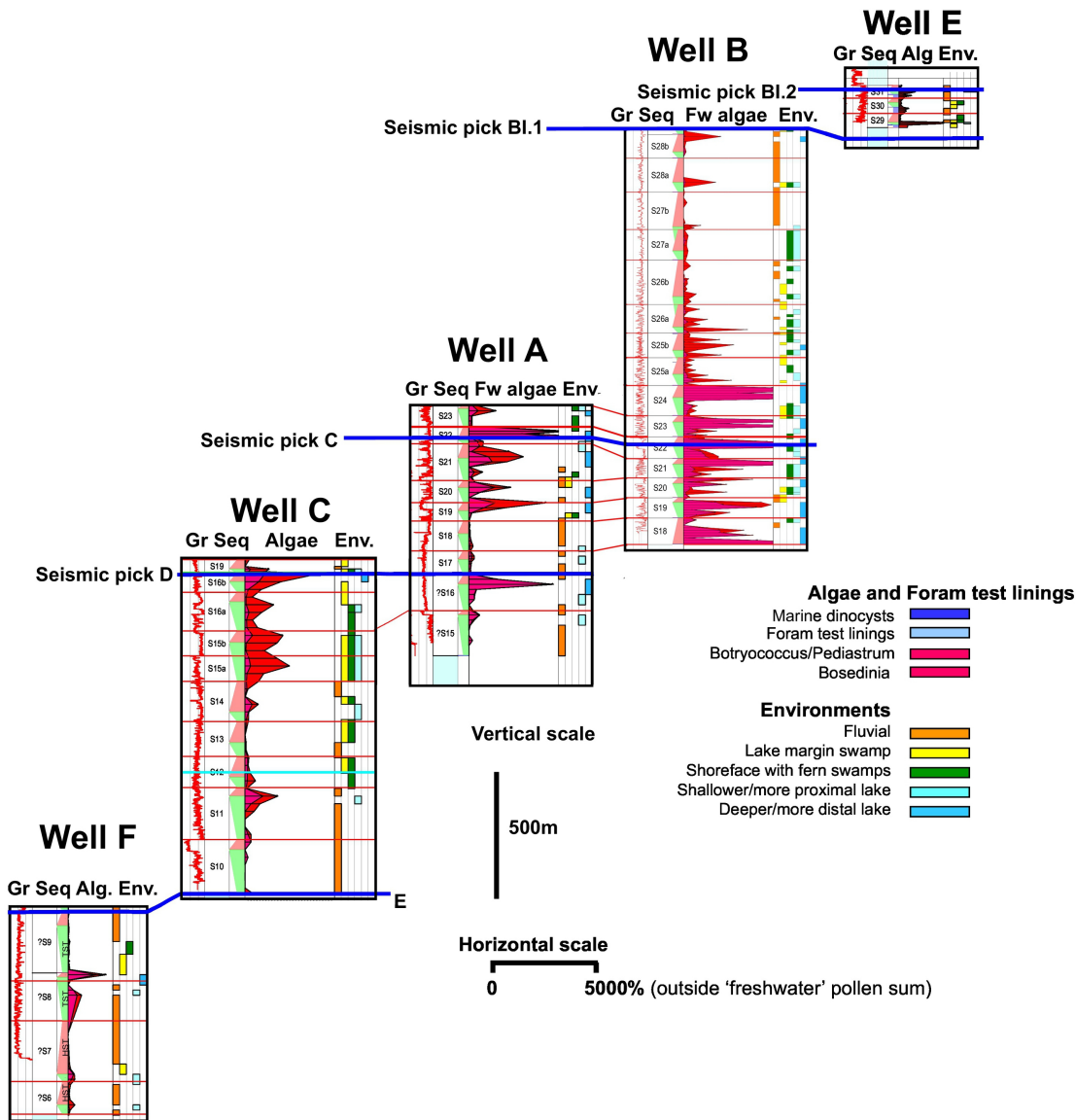


Figure 9

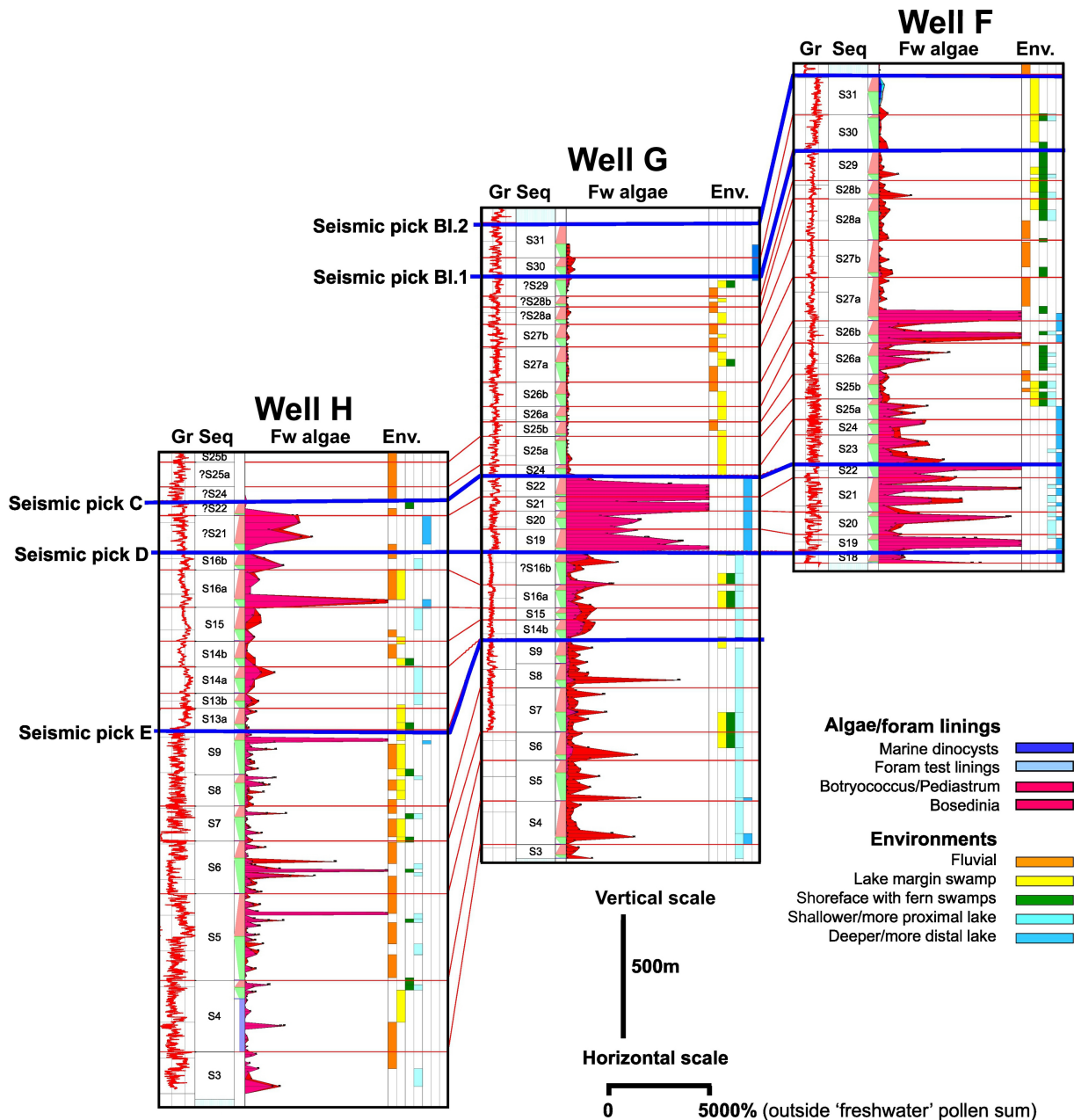


Figure 10

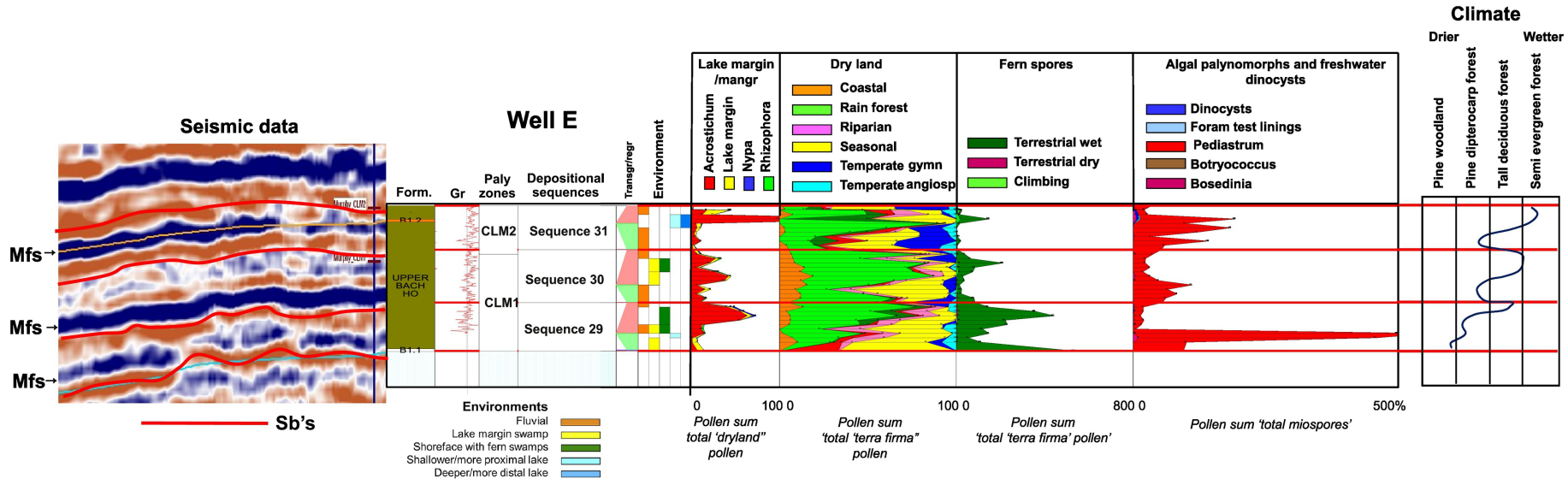


Figure 11



# Well C

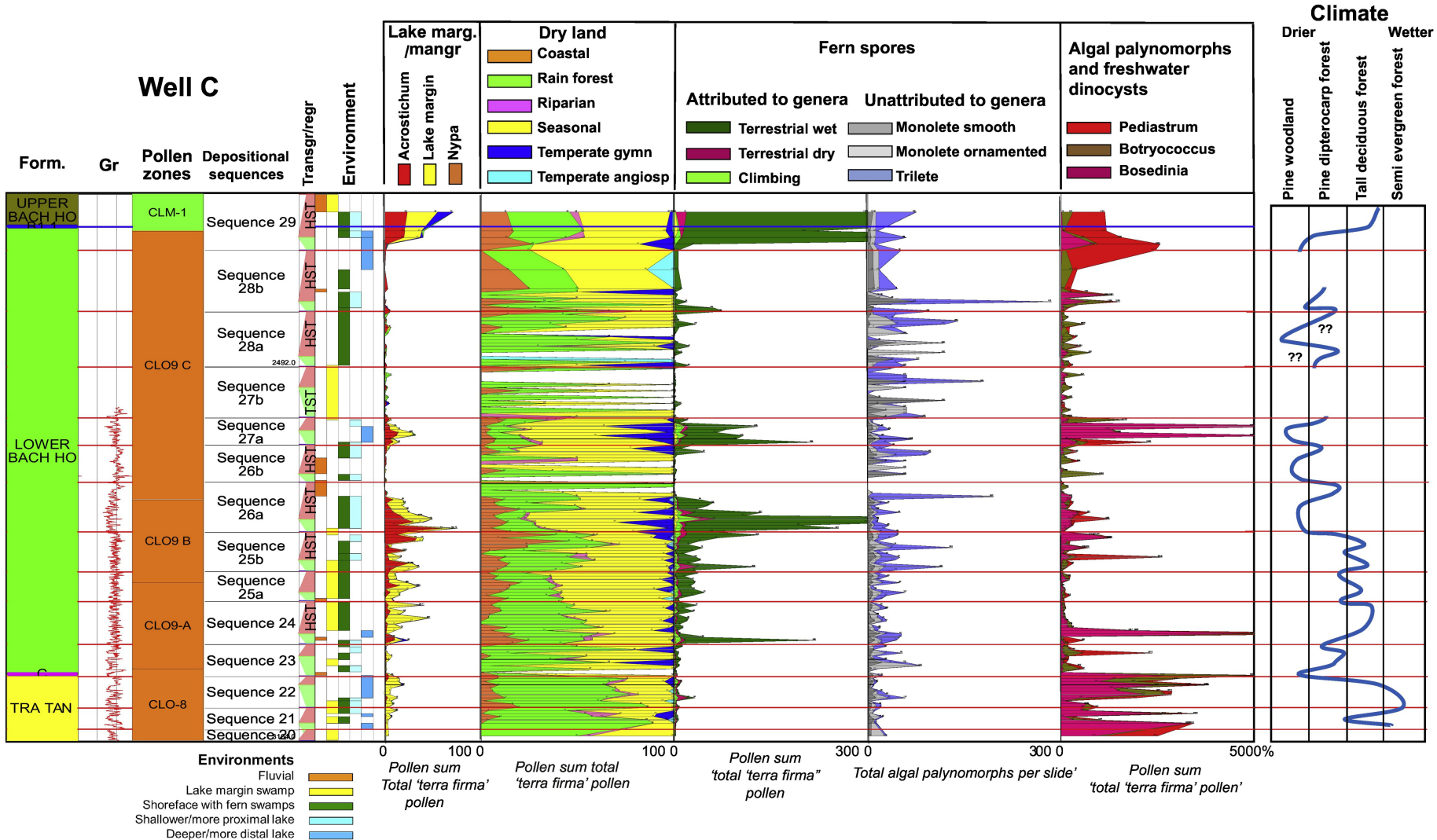


Figure 12



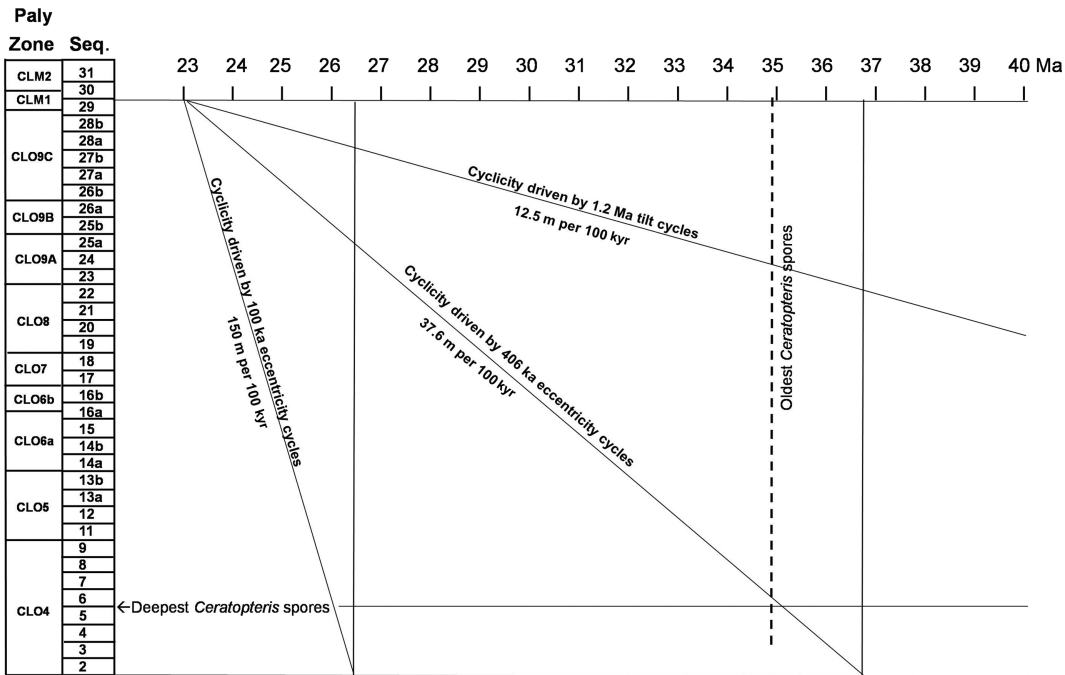


Figure 13

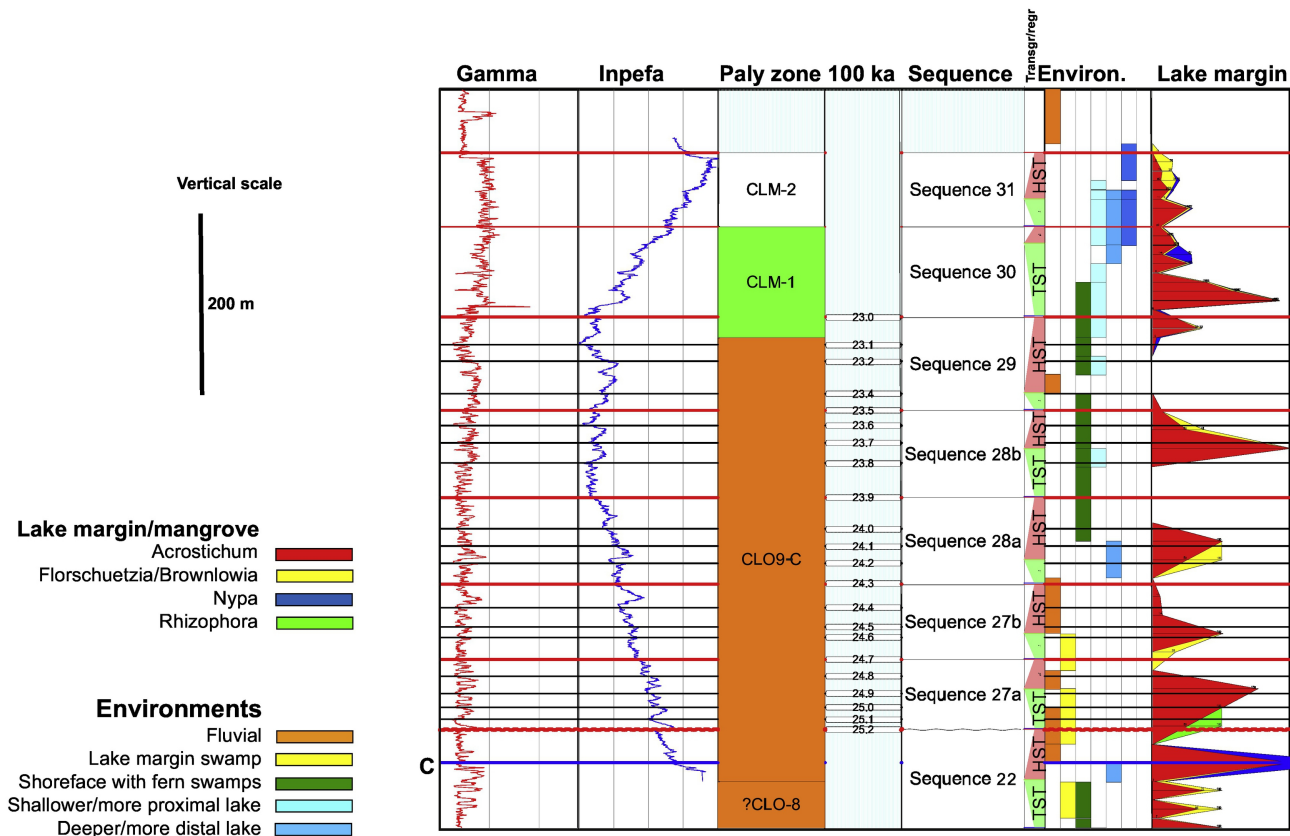


Figure 14

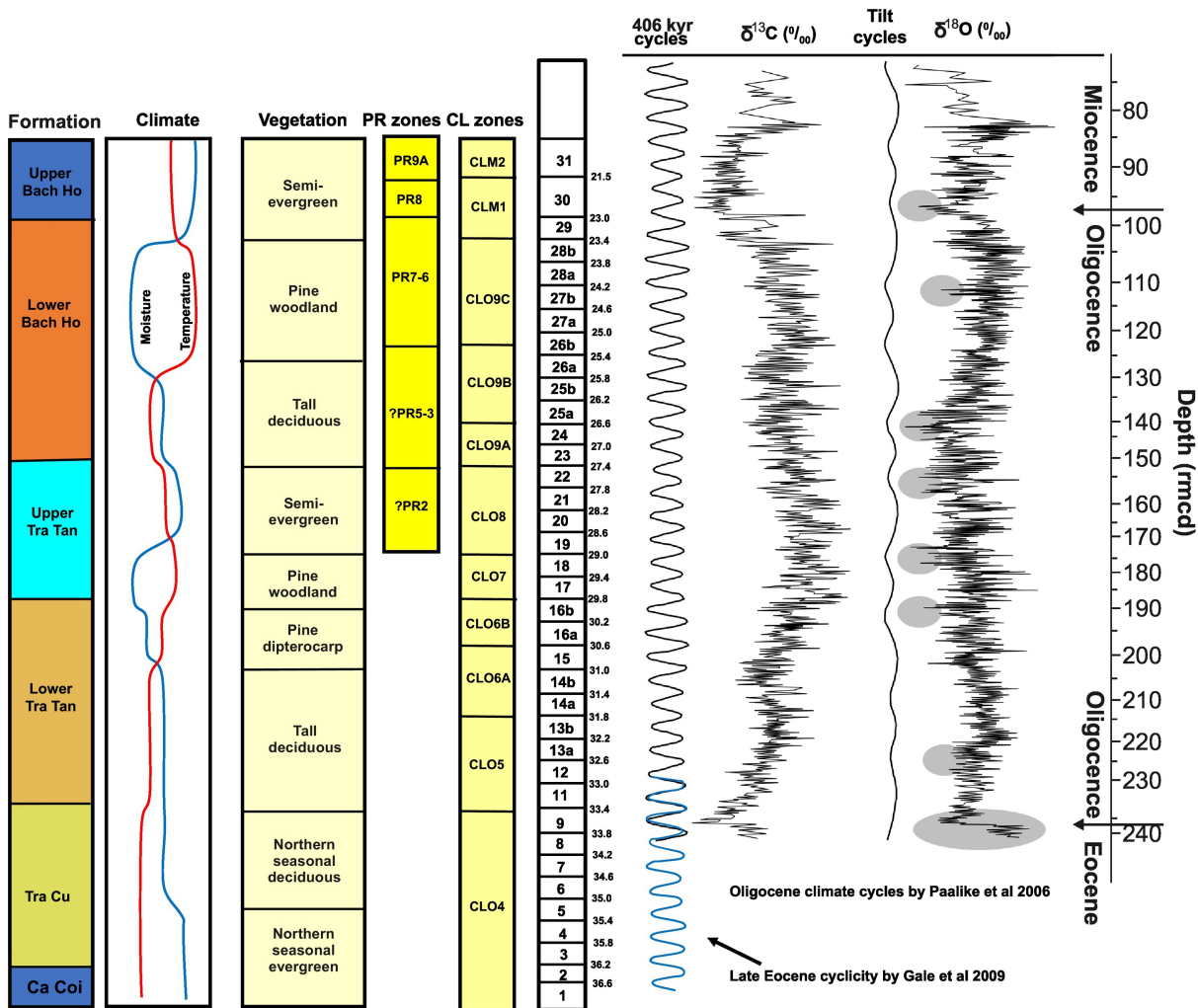


Figure 15

# Seismic line 'X'

Well B

Well A

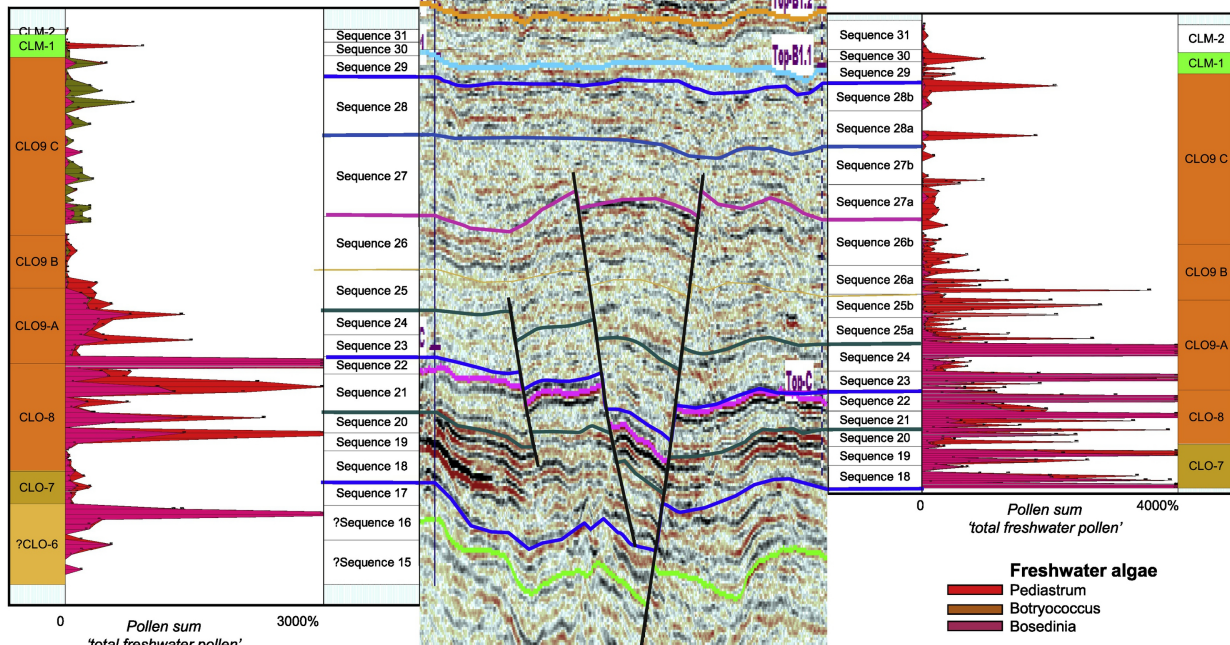


Figure 16

# Cuu Long Basin, schematic chronostratigraphy

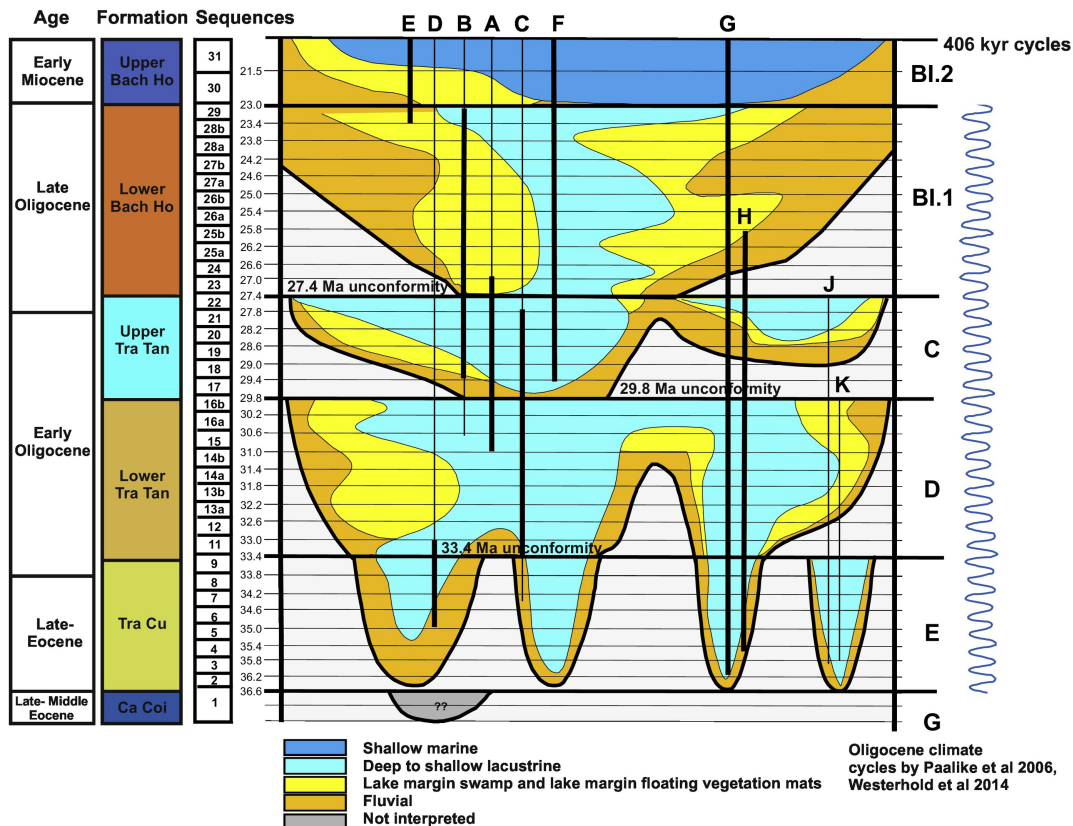
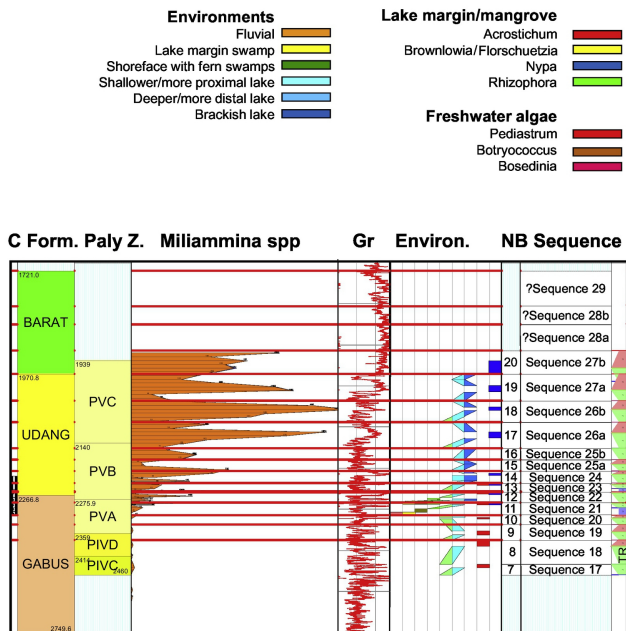
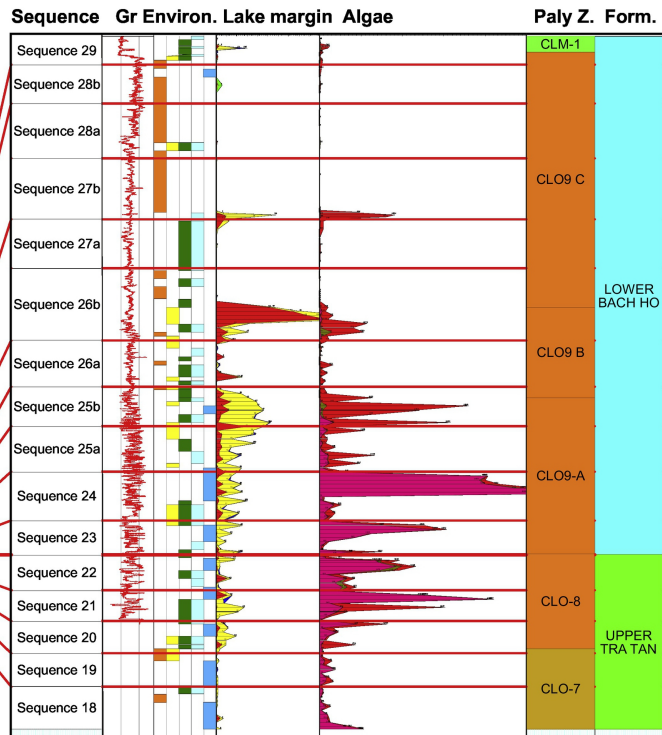


Figure 17



North Belut 5 (West-Natuna Basin)



Well A (Cuu Long Basin)

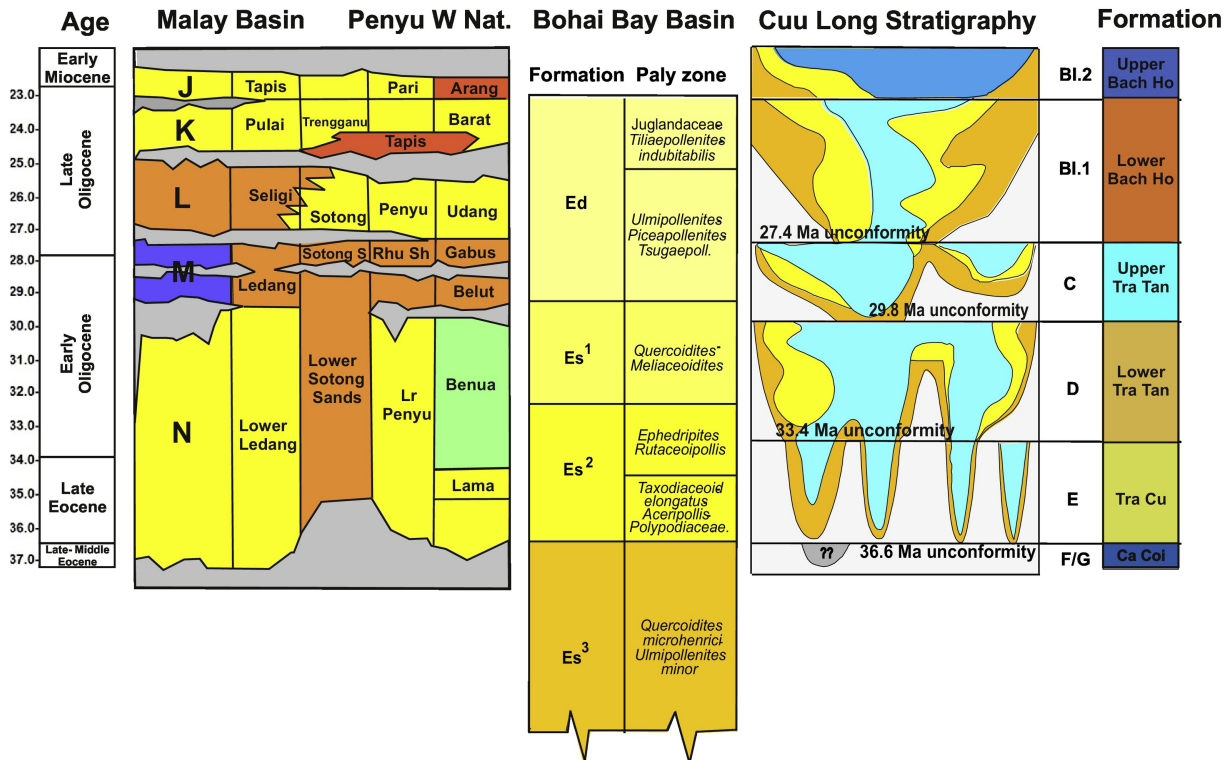


Figure 19